NASA TT F-10,204

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FLIGHT HANDLING QUALITY PROBLEMS POSED BY SWEPT-WING TRANSPORT PLANES WITHOUT TAIL UNITS

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Translation of "Quelques problèmes de qualités de vol posés par les avions de transport à aile elancée sans empennage"
Paper to be presented at the 28th Meeting
of the Flight Mechanics Group of AGARD

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON JUNE 1966

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ABSTRACT

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A new generation of swept wing, tail-less, and somewhat heavy planes is being born. These airplanes have many new features, being different from both delta winged warplanes and moderately swept wing transport planes. /1*

Some of these unusual features are analyzed from the viewpoint of the pilot's numerous tasks, and the applicability of some classic or new criteria is studied.

A somewhat wide scanning of the possible characteristics is made concerning the lateral flight qualities. This scanning shows the complexity of the problem and the mutual influence of the various criteria that come into play. Emphasis is put into the special low velocity type of behavior, in connection with the longitudinal flight qualities.

It is concluded that the critical points are different for these planes than for their predecessors, and that the standards of judgement must be rethought. As a whole however these flight qualities, while being different from those of their predecessors, compare favorably with them.

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*Numbers given in margin indicate pagination in original foreign text.

PART ONE

1.1 Introduction

From the very beginning of aviation a considerable amount of work has been done concerning the stability and flight qualities of airplanes. These problems involve the adaptation of man and aircraft to each other and are particularly complex for two reasons:

1) Man undergoes an evolution, a short term evolution (adaptation during the pilot's school period or during the training with a given airplane), and a long term evolution (adaptation to new types of aircraft); his possibilities of evolution are however not unlimited.

2) The airplanes undergo an evolution and the experience gained from one airplane generation is not automatically applicable to the next generation.

In other words, the flight quality regulations may become one of two things:

1) either obsolete documents

2) or modern documents, based however on insufficient experience, unless they can be reduced to the following sentence: "The airplane must be safe and easy to pilot".

From a more optimistic standpoint, the lack of really valid criteria does not necessarily mean that the knowledge of the problems has not progressed. This knowledge is however much more limited for somewhat heavy transport airplanes than for warplanes, and the uncertainty is increased still more by the unconventional nature of the most recent projects.

The appearance and later widespread use of black boxes, i.e. of automatic aids, has modified the nature of the problem without offering solutions, because of reliability considerations. This evolution has led to raising the question of minimum acceptable flight qualities that can be guaranteed when breakdown of the autostabilizer occurs. This is a problem which has shown up only recently. /2

To offset these difficulties the engineer has at his disposal more powerful means, such as:

1. a better understanding of the human pilot behavior and of the coupling mechanism between the man and his machine.

2. a more widespread use of simulation techniques.

The comments which follow have to do with longitudinal and lateral flight handling qualities of heavy transport planes having highly swept wings and low aspect ratios. They are the result of various studies made on several civilian transport plane formulas. We think however that most of these comments have a wider range of applications.

The present paper does not purport to be exhaustive. It only brings up a few points of the problem.

The theoretical studies made with a simulator or with an airplane of variable stability are being pursued but only the total experience gained will be decisive.

We have deliberately left out the points which raise few or no new questions. We have also completely left out aeroplasticity problems in spite of their importance, for the following two reasons:

1. The static or pseudostatic aeroelasticity must be taken into account in the planning but this does not change the criteria to apply.

2. The dynamic aeroelasticity (local accelerations due to the structural modes as created by sudden causes or by atmospheric turbulence) is an enormous subject which would require a whole special paper.

1.2 General Comments on Flight Handling Quality Criteria

A lot of confusion exists about flight handling qualities, because of their being relative. The validity of a given criterion is a function (which is sometimes explicit but often implicit) of a whole series of "boundary conditions". It is always difficult to bring to light with certainty the parameters which are hidden (even when extreme care is used) and which can preclude the conclusion of a certain experiment.

Take for example the problem of the longitudinal stability tolerated /3 by the pilot, as expressed by a judiciously chosen parameter (static margin, divergence time constant, etc.). In fact, the acceptable instability will be a function of many other parameters, such as:

- the nature and size of the atmospheric turbulence,
- the individual training of the concerned pilot,
- the collective (or historical) indoctrination of pilots of a certain epoch, taking into account the aircraft they had an opportunity to fly,
- the task performed by the pilot (VFR or IFR for example, cruising or approach, etc.),
- the other aircraft characteristics, for example: the lateral characteristics (in other words the degree of attention necessary for the other tasks he must perform)
- the duration of the task to be performed
- the airplane type and its mission
- the mechanical flight control and its balance, etc.

In what follows we propose to consider several aspects:

1. the unpiloted airplane flight handling qualities: natural behavior, free control stability, etc.

2. the ease of balancing a given flight situation : considerations of compensation;

3. the accurate piloting (the pilot acting accurately on the control loop);

4. the high amplitude maneuvers within the framework of the mission.

1.3 Weight and Aerodynamic Peculiarities of the Cases Considered

We will limit our study to fairly heavy planes, with a transport mission, highly swept wings, low aspect ratio and no horizontal tail unit. These configurations have the following general characteristics.

1. Inertial Characteristics

The inertia distribution around the three principal axes has gone through an evolution analogous to that of warplanes: the ratios of the inertias of pitch (B) and yaw (C) to the inertia of roll (A) have increased. This is due to the 4 swept wing and to the long and thin fuselage (for the purpose of reducing the frontal area). In some configurations the amplitude of this effect is limited by the arrangement of motors in pods under the wings.

In addition, since the mass is relatively high, the inertias of pitch and roll are very high too. The rigid as well as the flexible mode frequencies will have a tendency to decrease.

2. Aerodynamic Characteristics

The principal unusual aerodynamic characteristics are the following:

- a dihedral effect, strongly dependent on the pitch angle and unusually high at low speed;

- the directional stability (Cnj), having a tendency to decrease at the highest Mach numbers;

- relatively low roll damping;

- non-negligible secondary elevon effects ($C_z\beta$ and $C_n\alpha$);
- a generally important ground effect;
- a low lift gradient, but a very wide range of usable pitches.

The possible consequences of such a situation can be the following:

- on the lateral behavior:

relatively high roll time constants; a response behavior to aileron control somewhat different from that of a first-order system with strong intervention of the cross coupling (inertial coupling); a net coupling between the roll mode and the oscillatory mode (and possibly the spiral mode); the great roll velocities which are relatively easily obtained; a special turbulence behavior with pronounced roll excitation.

- on the longitudinal behavior:

relatively longer short periods and, in response to the elevator action, a significant "non-minimum phase" - like behavior, a reduced sensitivity to turbulence if reasonably high wing loads are tolerated, and at low velocities, a flight regime typical of the "second regime".

We shall review below some of these points.

PART TWO. LATERAL FLIGHT HANDLING QUALITIES /5

We shall consider in succession the various points of the flight handling quality criteria which we mentioned above, restricting ourselves again to the moderately heavy, very highly swept wing, airplane.

2.1 The Flight Handling Qualities of the Unpiloted Airplane

Transport planes very often make flights of long durations with the autopilot on and the pilot's hands off the controls. It is therefore the automatic pilot regulation which must be discussed.

The free control characteristics are even more interesting for two main reasons:

1. breakdown of the automatic pilot;

2. many other reasons which compel the pilot to have a manual control of the aircraft, but then this control serves as a check rather than an accurate piloting.

The characteristics relative to the convenience and accuracy of the control are mentioned later (see Section 3). Only the normal behavior (and not the behavior in case of breakdown) will be mentioned here. In case of various breakdowns, it can be thought that the pilot will attempt to control the airplane and the automatic pilot control is consequently less interesting. Various elements play a role in the case of automatic pilot flight. These are as follows.

2.1.1 The Spiral Mode of the Airplane

In spite of the fact that it is relatively easy to control an airplane having a highly unstable spiral mode, the latter characteristic seems to have been the primal cause of a certain number of incidents (or even accidents) in the past, as follows:

- start of the spiral becoming tighter, followed by a loss of the instrument flight control (IMC conditions) or by going beyond the flight range permitted by the plane (V_C or even V_D) leading sometimes to structural changes. The regulations are scant on this subject. /6

1. The French or American civilian specifications (References 1 and 2) and the French military specifications (Reference 3) do not specify any requirements.

2. The U.S. military specifications require that the motion be not too unstable in the following:

a) in cruising or approach configurations, the amplitude must not double in less than 20 s.

b) in other configurations it must not double in less than 4 s.

3. The recent Anglo-French SST Standard specifies a similar requirement for the supersonic civilian airplanes, i.e. the amplitude must not double in less than 15 s.

It seems anyway that to prohibit an excess of spiral instability under the frequently met flight conditions (i.e., conditions including sufficiently reliable aids to the pilot) is a quite reasonable requirement. Since the acceptable limit is a matter of judgement, only the systematic use of a great number of various planes can lead to significant information.

The type of airplane of interest to us presents itself in a particularly favorable way from that standpoint. Indeed, the relative values of the various coefficients, and especially of C_{lj} and C_{nj}, give the airplane a guarantee of stable spiral mode, especially at low velocities (high increase of C_{lj} with the pitch).

Figure 1 shows an example of the kind of results obtained. Even if strong changes of aerodynamic coefficients are supposed to happen, the situation remains favorable, since the spiral mode never becomes unstable. The same is true when autostabilizers are used (which, in the worst case, may lead to indifference).

2.1.2 Role Played by the Balancers

We must however avoid any excessive optimism. An inaccuracy in the balance of the two lateral surfaces, and especially of the ailerons, entails for the pilot the same difficulties as a spiral instability.

It is forseeable that the low aspect ratio airplanes will have a very sensitive lateral control, especially at high velocities. A very high degree of quality will be required in the construction of the mechanical, hydraulic and electric systems made up by the flight control. The technological problem /7 can in this case be more important than the aerodynamic problem.

2.1.3 Oscillatory Mode

The oscillatory mode damping is concerned with the automatic control behavior. The various existing specifications offer some requirements (references 1 through 5). There are reasons to think that these requirements are dictated by the piloting proper of the airplane rather than by the automatic control flight. Because of the periods encountered (1 to 10 s) with all types of aircraft (periods which are clearly shorter than those of the phugoid longitudinal mode), it can be inferred that an unstable motion is unacceptable in normal flights and that a minimum of stability is required. Then, what is the value of this stability minimum? It is very difficult to determine it, since other reasons have led in the past to not accepting unstable motions. It is however probable that the damping time (for example t 1/2) is a better criterion than the number of damped cycles (C 1/2).

The airplanes of today have oscillatory mode characteristics which are different in many respects from those of their predecessors. These differences will be discussed below in section 2.3.4 and we think that the discussion given there sums up the problem.

2.2 Airplane Balance

The more or less greater ease with which an airplane can be balanced for a trimmed flight regime plays a role which is certainly important in respect to estimating the flight handling qualities of a piloted airplane, especially in the case of transport missions. It can also influence the flight safety, an example of which was given above (see 2.1.2). This role has not been correctly interpreted in the past. The specifications undoubtedly specified the flight conditions under which the balancing must be made (see for example refs. 1 and 2). They gave rather poorly the characteristics for a good balance, by emphasizing either the balance speed feedback error (refs. 1 and 2) or the mechanical qualities of the flight control (ref. 3).

A poor balance is undesirable for three reasons. /8

1. It can have consequences analogous to those of an instability having long period characteristics.

2. It increases the load on the pilot, who is spending his time trying to find a better balance, with less time left for other tasks.

3. It leads to more difficult accurate piloting, should the latter be necessary.

The following items help the quality of balance:

1. The accuracy and the faithfulness of the flight control systems. By "system" is meant all the mechanical, hydraulic and electric elements which make up the flight control, including friction, elasticity, restitution property of possible artificial forces, accuracy of the servo-controls, quality of the synchros, etc.

2. The stiffness of the aerodynamic effects, the magnitude of the "dihedral effect" C_{lj} and of the "directional stability" C_{nj}. In other words, the characteristics of the airplane in rectilinear side-slip flight.

3. The possibility of creating or changing small asymmetries. The power plants play the top role as far as their position on the plane is concerned (position with respect to the plane of symmetry, displacement in height, sensitiveness of the pull to various parameters, accuracy and range of the motor regulation, etc).

We will concentrate on the following points concerning highly swept wing transport planes:

1. Special importance of excellent construction of the flight controls because of the control surface effectiveness for small displacements (especially that of the aileron).

2. Favorable influence of relatively high aerodynamic effects (C_{l_j} and C_{n_j}).

3. Variable effect of the power plants, depending on their distribution on a given airplane. This effect can be significant due to the complexity of the power plants and of their regulation. Since Item 2 is favorable, Item 1 will probably condition the balance quality.

2.3 Precision Piloting /9

2.3.1 General Comments

The precision piloting poses the most delicate flight handling quality problems. The case in question is the one where the pilot carefully controls the plane for the purpose of accomplishing a well defined and precise task. The plane characteristics and the more or less happy adaptation of the plane and pilot play a role. This type of piloting was also the focus of most flight handling quality studies undertaken in past years. In spite of this, as will be seen below, our knowledge remains quite bounded because of the great number of problems present and of the tasks to accomplish.

For transport planes, the problems raised in Section 1 are hidden in the operation by the general use of the automatic pilot. The problems we have raised in Section 2 have to do mostly with the mechanical characteristics of the flight controls.

The cases which require precision piloting are the following:

1. The maintenance of the attitude and course (and indirectly, of normal acceleration) under visual or instrumental flight conditions.

2. The accurate control of the flight path in the approach or landing phases (especially IMC).

3. The take-off and landing maneuvers proper.

If an artificial autostabilization is used (which is generally the case in high performance planes) the flight must be studied with and without autostabilization. In particular, the problem of tolerable minimum behavior under the somewhat rare emergency conditions, in cases of critical breakdown of the aids to piloting, deserves a special examination. This is a relatively new problem, one that the generalized use of black boxes has brought forward into the realm of current problems. The use of these black boxes can often become a major problem.

We shall discuss in what follows the forseeable effect of the special characteristics of highly swept aircraft.

/10

2.3.2 Time Constants of the Pure Roll Mode

The time constant T_R of the pure roll mode may be unusually large for a transport plane of low aspect ratio. This is due to the relatively low value of the roll damping (C_{lp}) connected with the low aspect ratio, combined with a roll inertia which remains high if the engines are placed in one or several housing (pods) under the wings. This situation has rarely been critical for delta winged military planes, since their engines were generally located in the fuselage. This situation has shown up only in special configurations having high roll inertia.

Theoretical and simulator (refs. 6 and 7) studies made by approximating the airplane motion to a one-degree-of-freedom (i.e., the roll) motion have shown that an increase of T_R could lead to a noticeable deterioration of the flight qualities.

It is certain that a plane responding to a warping maneuver by a practically pure roll motion with a very short time constant, i.e. a few tenths of a second (which leads practically to a roll velocity control), is ideal. This ideal case has been obtained for many years (this ideal is referred to by a few pilots by the expression: "the airplane remains perpendicular to the stick"). The lateral flight qualities depend then only on the effectiveness of the warping.

Leaving this latter problem aside for a moment and assuming the one-degree-of-freedom approximation to be valid, the studies have shown that when the time constant increased markedly to above 1 s the pilot's opinion deteriorated. This seems to be connected with the fact that the control resembles more and more an acceleration control, which is well known to be more difficult than a velocity control. Reference 6 shows for fighter planes the satisfactory limit to be around 1.2 s and the limit acceptable in emergency poorly defined but equal to at least 5 s. Since in fact it is the ratio T_R/τ which is in question (where τ is the pilot's time lag) and since τ does not change much, one can expect that these limits depend little on the type of aircraft, but do depend solely on the maneuver to be performed. Taking into account the fact that rapid maneuvers are less frequent in transport planes we have the following: /11

1. Reference 5, which suggests 2.5 and 5 s.

2. Reference 8, which suggests 2 and 8 s.

Figure 1 shows typically the values of the roll time constant for various flight cases. It can be seen that, if the values of T_R are very often relatively large they are however not such that a tolerable control would not be possible during a breakdown of the autostabilizer. The use of a roll damper permits to bring T_R to more common and low values (fig. 2).

2.3.3 Problems Concerning the Spiral Mode Time Constant (T_s)

In the past the spiral mode has created some problems, but these had rather to do with open loop piloting, with the pilot performing only a check. This case was discussed before in Section 2.1.1. The accurate control has never, as far as we know, created problems. It should be said that most airplanes have spiral characteristics close to the indifference (stable or unstable mode with large time constant). Recent studies have led to the discovery of some control problems when this was not the case (ref. 7).

a) Theory has shown, and experiment has confirmed, that an airplane having a highly unstable spiral mode (amplitude doubled in less than 1 s., ref. 9) remained controllable, although quite uncomfortable.

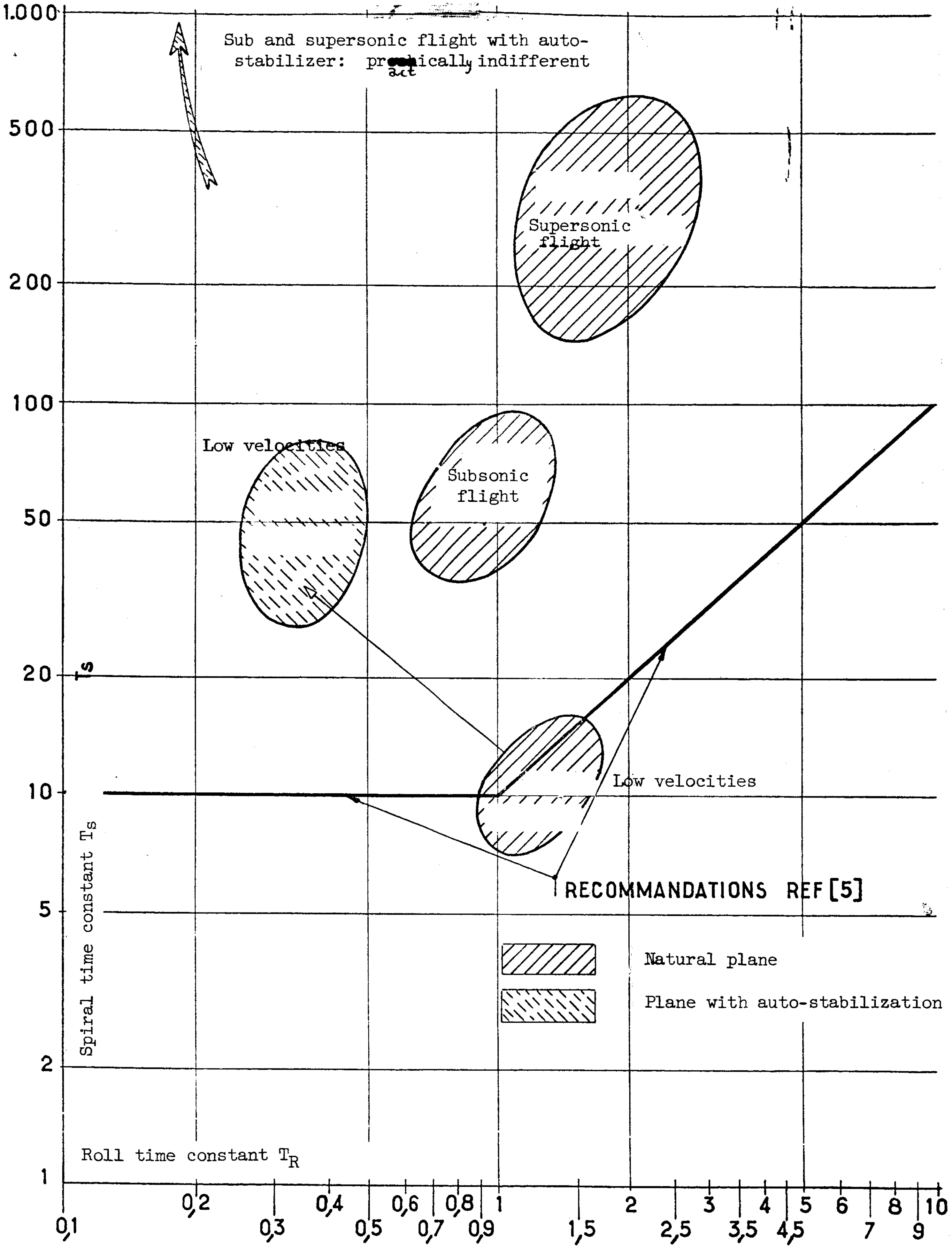
b) A value of T_S too low (whether stable or unstable) is uncomfortable for two reasons:

1. it assumes a great constant action of the pilot in a continuous turn;

2. the actions performed by the pilot, for controlling either the lateral attitude or the course, are located in the same frequency band and could more or less interfere. Reference 5 recommends for normal flights with autostabilization $|T_S| > 10$ $\left|\frac{T_S}{T_R}\right| > 10$ (see fig. 1). Analogous recommendations are found in reference 8.

The characteristics of the planes we are interested in correspond to /12 spiral modes always stable, and if the time constants T_S are sometimes low (figs. 1 and 2), due to a fairly strong stability, they are not sufficiently low to create problems. With autostabilization the stability of the spiral mode is reduced, and this criterion is better met.

We conclude, by comparing this discussion to that of Section 2.1.1, that the situation concerning the spiral mode is particularly favorable.



Sub and supersonic flight with auto-stabilizer: practically indifferent
Supersonic flight
Low velocities
Subsonic flight
Low velocities
RECOMMANDATIONS REF [5]
Natural plane
Plane with auto-stabilization
Spiral time constant T_S
T_S
Roll time constant T_R
1.000
500
200
100
50
20
10
5
2
1
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1
1,5
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2,5
3
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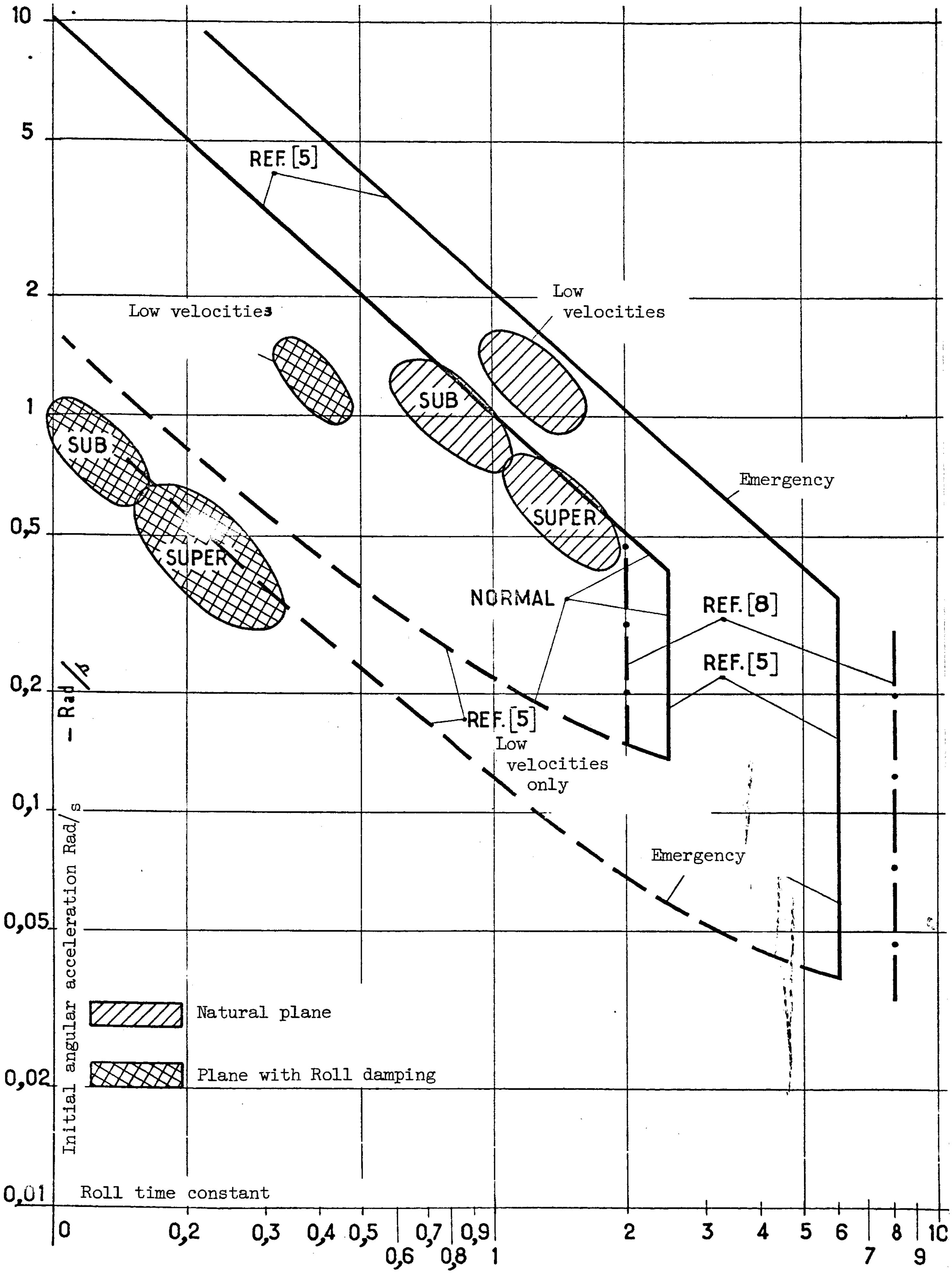
8
9
10

Figure 1



10
5
2
1
0,5
0,2
0,1
0,05
0,02
0,01
REF. [5]
Low velocities
Low velocities
SUB
SUPER
SUB
SUPER
Emergency
NORMAL
REF. [8]
REF. [5]
REF. [5]
Low velocities only
Emergency
— Rad/s
Initial angular acceleration Rad/s
Natural plane
Plane with Roll damping
Roll time constant
0
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1
2
3
4
5
6
7
8
9
10

Figure 2

2.3.4 Problems Connected to the Control of Lateral Oscillation

The problems created by the control of the lateral oscillation have led to much work in the past few years, but these problems are still not completely solved.

When the pilot controls the plane under a disturbance of atmospheric origin, he wants to control the lateral attitude and consequently (with almost no slip) the course. The lateral oscillation is bothersome to the pilot. It can be thought that, in the first approximation, the comfort of the plane will be greater, provided the following applies:

1. the oscillation is more naturally damped;
2. it is easier for the pilot to damp it;
3. the warping motions which are necessary to insure the lateral control excite the oscillation to a lesser degree.

Before, the only criteria proposed for conventional, straight winged airplanes were the damping criteria. The oscillation had a fundamental yaw component which the pilot would damp fairly easily with the rudder, and the only parameter which seemed to have any effect was therefore the damping.

The highly swept airplanes and the high altitude flights have led to a tendency to reduce the damping (whence the use of yaw dampers) and to increase the roll in the motion. The tendency of the pilot to "counter with the stick" was increased and some possible control difficulties have shown up.

Based on somewhat fragmentary tests, the standards have used a minimum damping which varies either with the ratio ϕ / Ve (see ref. 4, fig. 3) or with the ratio p/r (see ref. 3). Roughly valid for airplanes of the same family, these criteria have been found at the outset to be insufficient to classify the airplanes, with the pilots mentioning "coordination difficulties" upon starting or

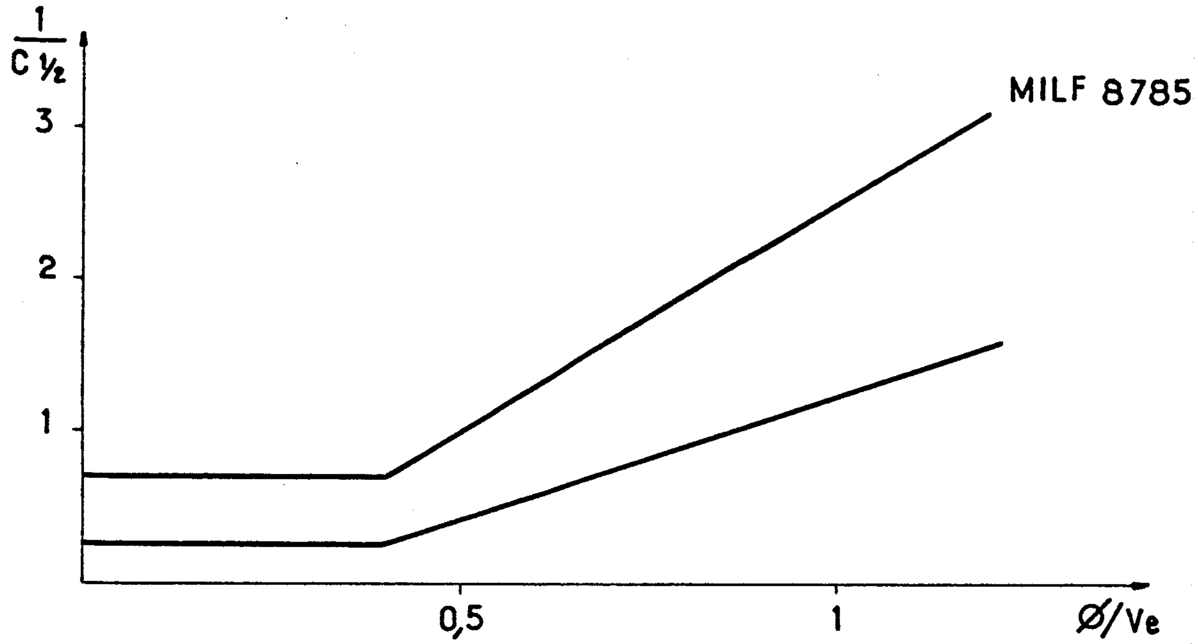


Figure 3

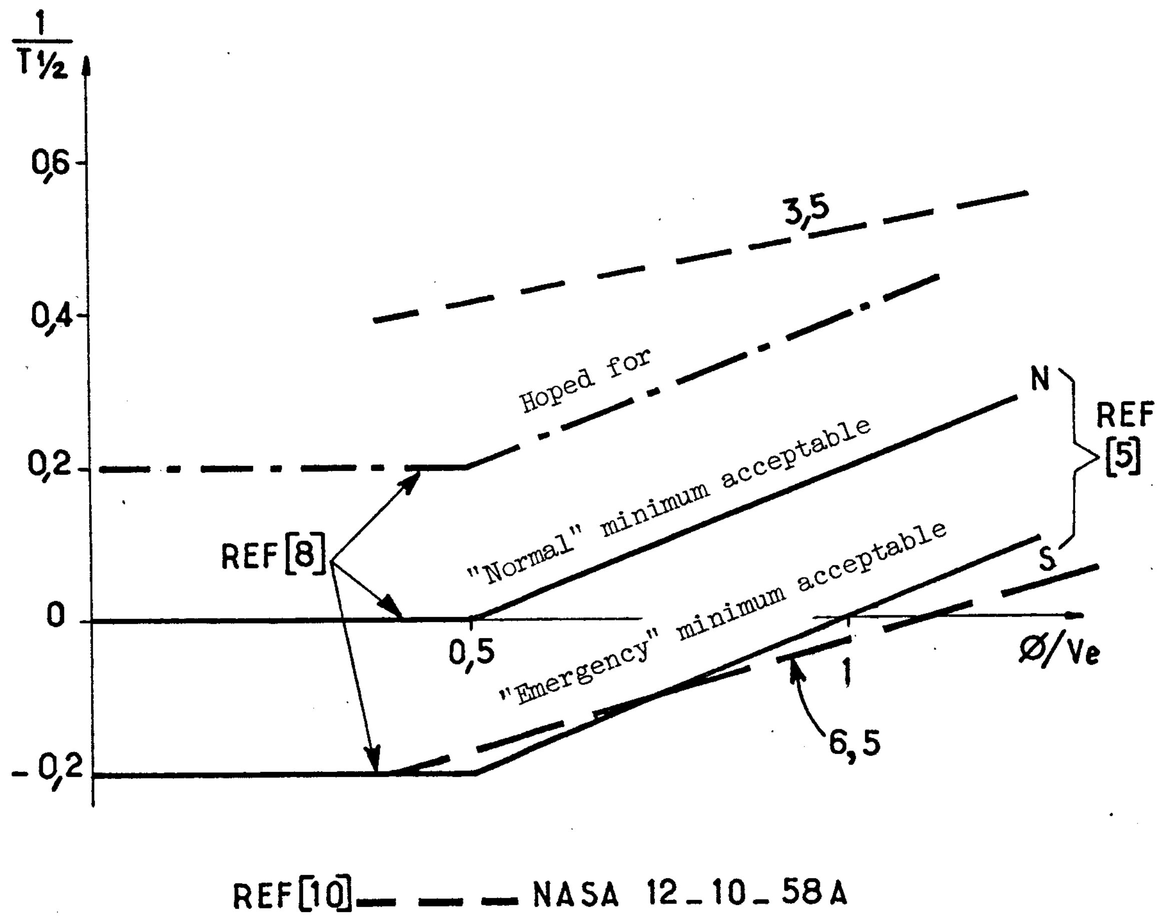


Figure 4

ending a turn. The interactions between the modes would cause an effect, /13
and especially the yaw, induced by the warping motion.

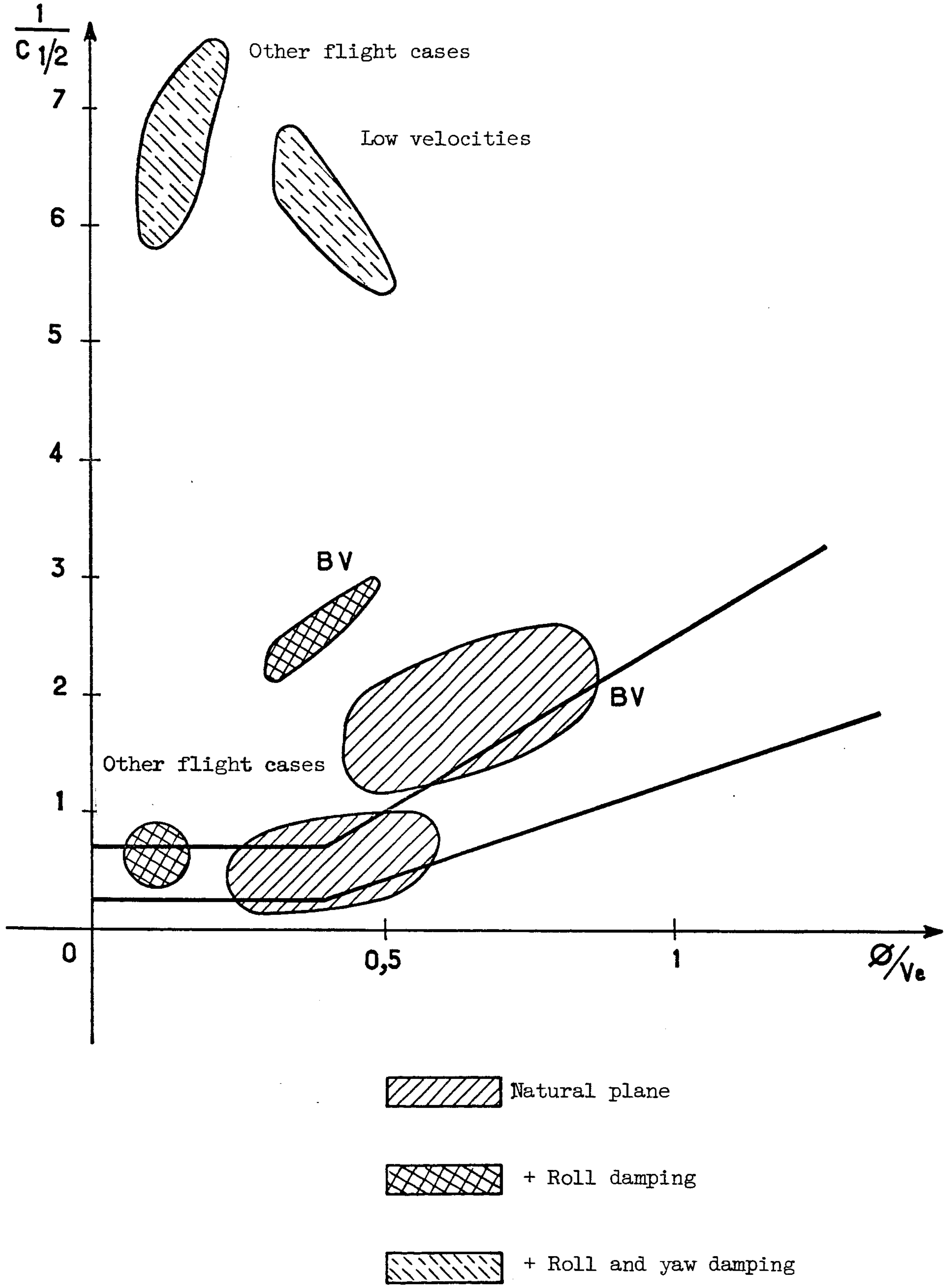
The tests described in reference 10 have shown that the requirements of reference 4 were excessive, at least as far as the approach is concerned, if the coupling effects were reduced to a minimum. The tests have yielded the limits shown in figure 4.

Reference 8 has suggested limitations which have been reused in the SST Standard No. 5 (ref. 5), based on the previous result and on an analysis of existing heavy weight transport planes. The minimum tolerable breakdown levels of references 8 and 10 are very close. The normal configuration minimum acceptable of reference 8 is perhaps insufficiently conservative, if only for reasons of "free control flight".

The coupling effects must be considered and various criteria have been proposed. Reference 7 introduces the $\omega\phi/_{\omega d}$ criterion and reference 11 studies the experimental results. In fact the $\omega\phi/_{\omega d}$ criterion measures to a certain extent the amount of lateral oscillation provoked by the motion of the ailerons. If $\omega\phi/_{\omega d} = 1$ and $\xi_\phi = \xi_d$ this excitation is zero. In addition, the influence of this effect decreases if the damping increases. This is indeed what the criteria taken from reference 11 say. These criteria are shown in fig. 8. Reference 5 uses an analogous criterion but its expression is more vague.

If we now consider the very highly swept transport planes, we notice that they will have a behavior very different from that of the subsonic planes of the past generation.

- The natural airplane has generally much better damping characteristics, always superior to the minimum level with breakdown, and almost always superior to the normal minimum level.



$\frac{1}{C\,1/2}$
Other flight cases
Low velocities
7
6
5
4
3
BV
2
BV
Other flight cases
1
0
0,5
1
ϕ/V_e
Natural plane
+ Roll damping
+ Roll and yaw damping

Figure 5

- The use of dampers (and especially of roll dampers) greatly improves the situation (fig. 5 through 7).

- Except at low velocity the coupling problems are almost nonexistent ($\omega\phi/_{\omega d} \neq 1$) and the use of the damper changes little this ratio, but increasing the damping strongly makes the characteristics completely satisfactory.

Figure 8 shows the comparison with the criteria of reference 11. This comparison leads to analogous results.

2.3.5 Efficiency of the Control Surfaces /14

This is the last point which we consider. The efficiency of the control surface, meaning what is usually called in vague terms "maneuverability", plays an important role in the estimation of the flight qualities. This role is due to several factors, as follows:

- The minimum level of acceptable stability is a function of the effectiveness of the "tool" which the pilot has at his disposal to control his machine. This is particularly true in cases of instability (see for example the criteria applied to helicopters or ADAV in stationary flight).

- The atmospheric turbulence effects must be controlled by the crew.

- Maneuvers of a certain amplitude or rapidity are necessary for operational reasons (for example the bayonet in approach).

Ailerons

The effects of roll time constant are connected with the time constant T_R of the roll motions. This has been discussed in Section 2.3.2. We have seen that, as long as this constant is small ($T_R < 0.5$ s for example) the airplane responds, from the pilot's standpoint, to the ailerons as a velocity control. The pilot's opinion is then necessarily connected with the time necessary to reach a certain lateral attitude.

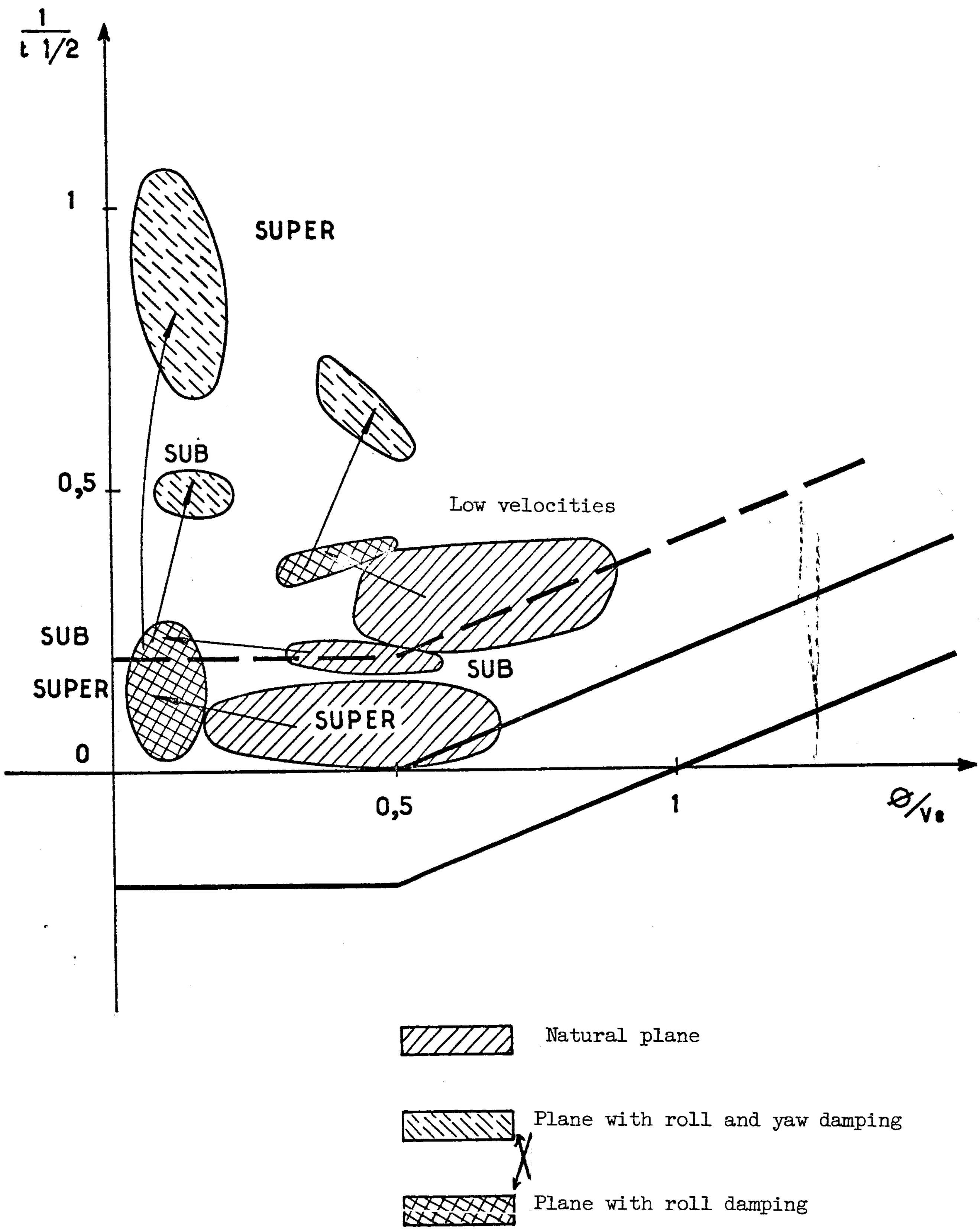

1/t 1/2
1
0,5
0
SUPER
SUB
SUB
SUPER
Low velocities
SUB
SUPER
0,5
1
Ø/Ve
Natural plane
Plane with roll and yaw damping
Plane with roll damping

Figure 6

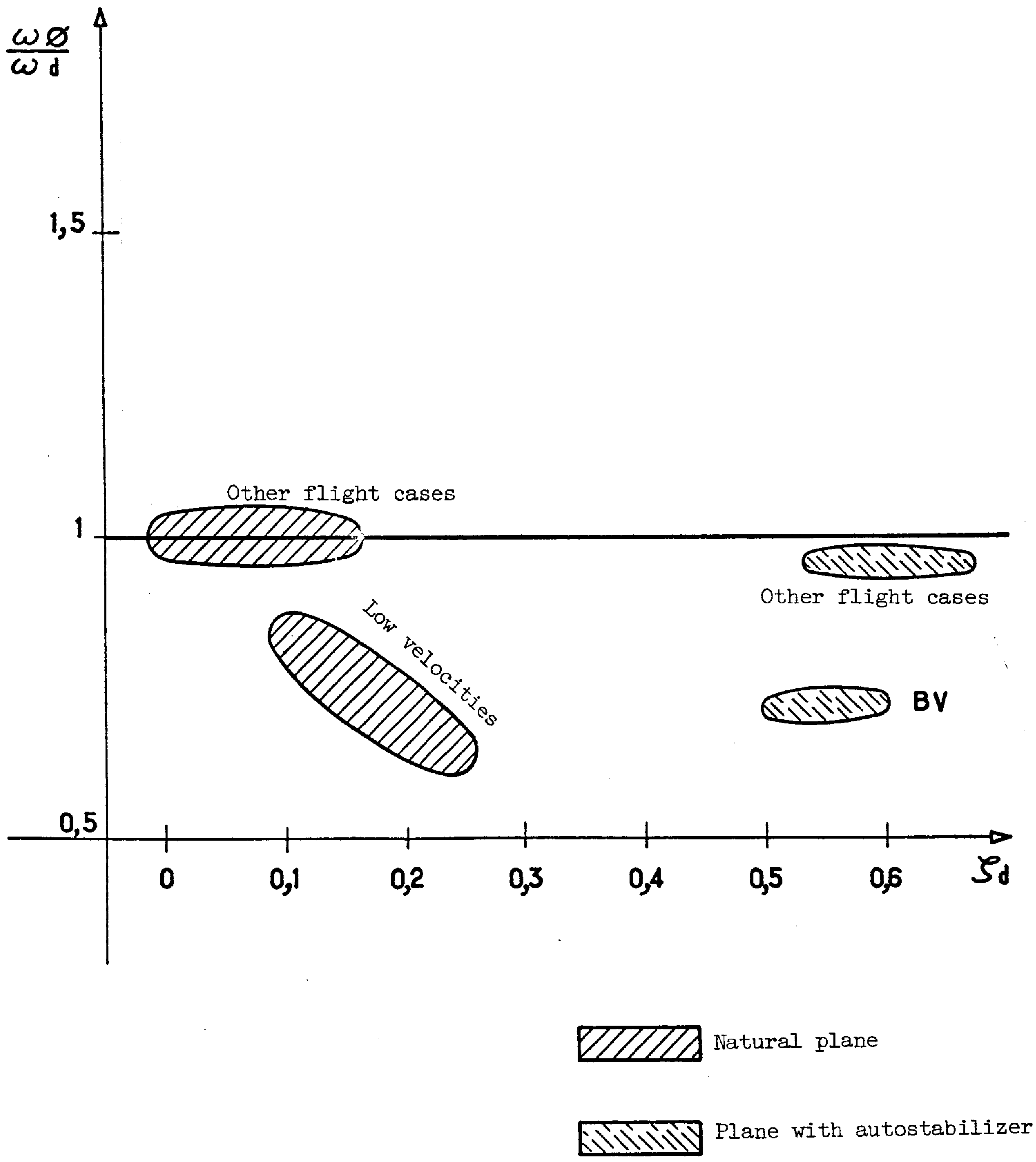
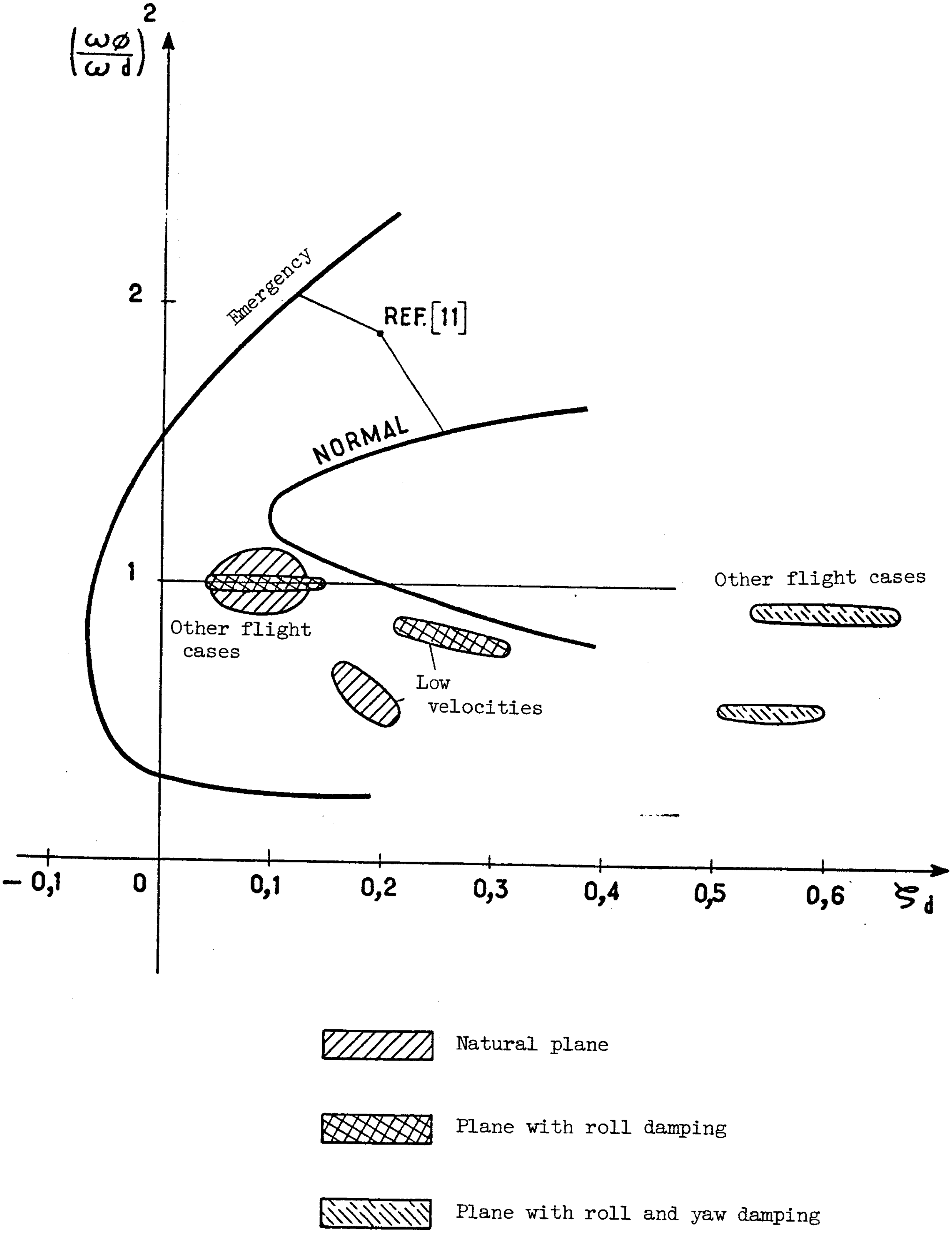

$\frac{\omega_\emptyset}{\omega_d}$
1,5
1
0,5
0
0,1
0,2
0,3
0,4
0,5
0,6
ζ_d
Other flight cases
Low velocities
Other flight cases
BV
Natural plane
Plane with autostabilizer

Figure 7



$\left(\frac{\omega\phi}{\omega_d}\right)^2$
2
1
Emergency
REF.[11]
NORMAL
Other flight cases
Other flight cases
Low velocities
– 0,1
0
0,1
0,2
0,3
0,4
0,5
0,6
ζ_d
Natural plane
Plane with roll damping
Plane with roll and yaw damping

Figure 8

The corresponding criterion is a function of the type and of the mission of the airplane. In this way minimum roll velocities have been set for warplanes. For transport planes it seems that the approach case is the most exacting.

The statistics of reference 8 seem to indicate that the satisfactory limit is around 6.5 s for 60° attitude change and the acceptable emergency limit is around 11 s for the same change of attitude. When T_R becomes relatively large ($T_R \gg 0.5$ s) the lag becomes sizable and a greater efficiency of the aile- /15 rons is required.

If the response of the airplane is very different from that of a "one-degree-of-freedom", the formulation of these criteria cannot be valid (case when $\omega\phi/_{\omega d}$ is very different from 1 and ξ_d is small, or case when T_S/T_R is too small). But then other difficulties can show up and the time of swing, whether a necessary condition, is certainly not a sufficient one.

On the other hand, and excessive effectiveness can also be unacceptable, by making the lateral control too sharp. This effect, which seldom occurred in old planes, is much more likely to occur in low aspect ratio and highly swept planes, i.e. planes whose aileron effectiveness could be decided by cross wind considerations at take-off and landing.

In fact, the laws of artificial control forces on these airplanes (which are necessarily equipped with servo-control) can, in a certain way, cure these difficulties.

The criterion shown in figure 2 is proposed in reference 5, from a compilation of all these conditions. For flights other than at low velocities a change of lateral attitude of 30° in less than 2 s is proposed, this last condition being perhaps needlessly severe. Figure 2 shows typical airplane characteristics of the formula under consideration, with and without autostabilizer:

- the natural airplane seems to be satisfactory in all flight cases except at low velocity (where it remains acceptable);

- the use of dampers (especially roll dampers) permits us to obtain a good behavior in all cases.

Directional Control Surface (Rudder)

We shall not mention this subject since it poses no new problems. The efficiency is conditioned by the motor breakdown problem and by the ground control.

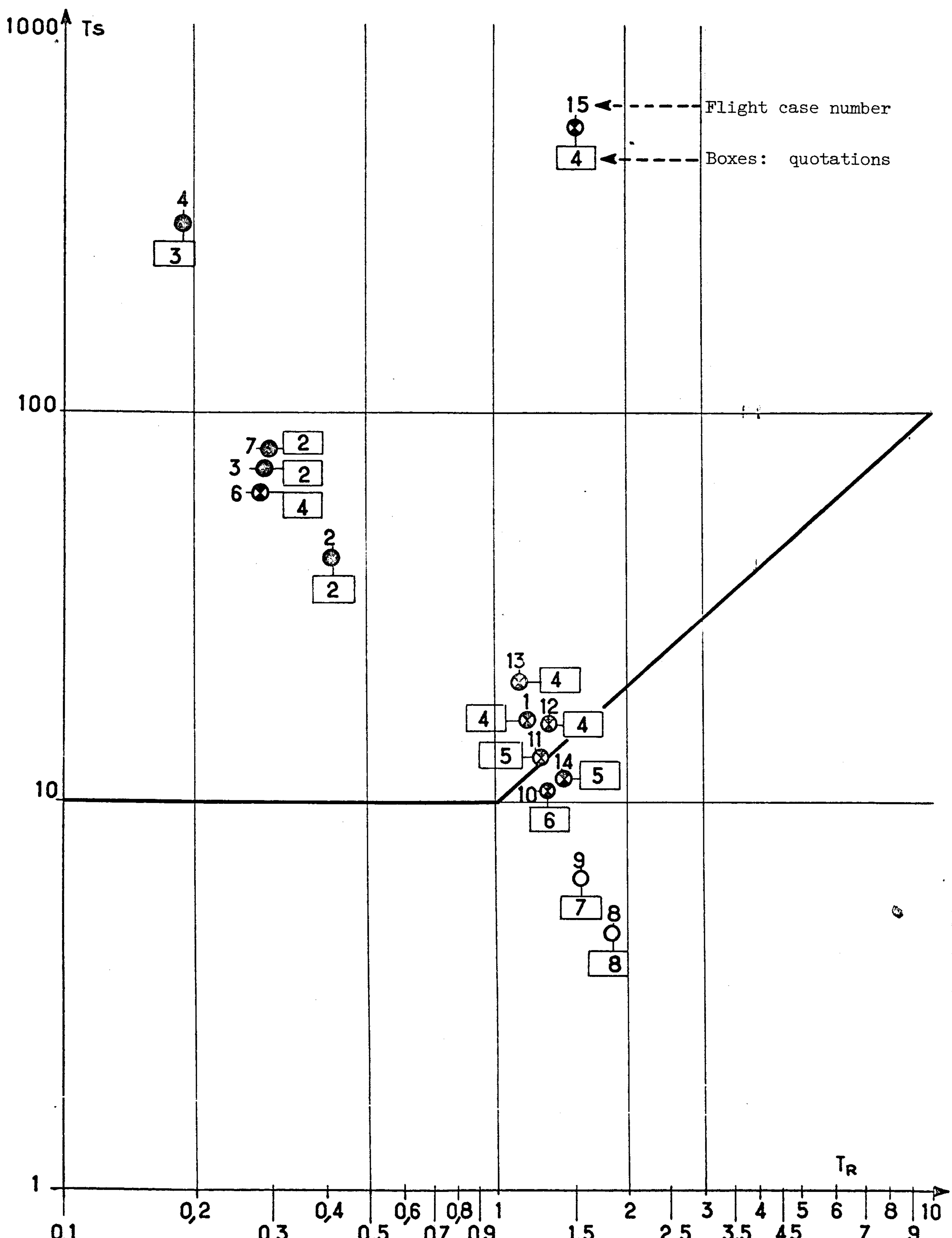
3.6 Simulator Studies

A certain number of tests were made with a fixed cockpit simulator equipped with a high altitude visual system (projection of a horizon on a hemisphere). In these tests no systematic goal was set. The tests led however to a certain amount of useful information. Fifteen flight cases have been studied, all /16 representing approach configurations, except case No. 15. We have used the same representations of figure 1, 6 and 8 on figures 9, 10 and 11.

Use was not made of a numerical scale of quotation (Cooper scale). A relative classification was possible in many cases and figures ranging from 2 to 8 have been quoted. It should be emphasized that this is an approximate quotation, almost coinciding, from the pilot's commentaries, with the Cooper scale at values around 3.5 (limit of normal acceptable) and around 6.5 (limit of emergency acceptable).

The general tendencies reported in Sections 3.2, 3.3 and 3.4 below have been seen to occur.

1. The difficulty of lateral control, associated with the large values of T_R, has immediately shown up (piloted nondivergent surge). No case however was critical enough to be judged unacceptable up to the largest experimental values



Ts
1000
100
10
1
T_R
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1
1,5
2
2,5
3
3,5
4
4,5
5
6
7
8
9
10
Flight case number
Boxes: quotations

Figure 9

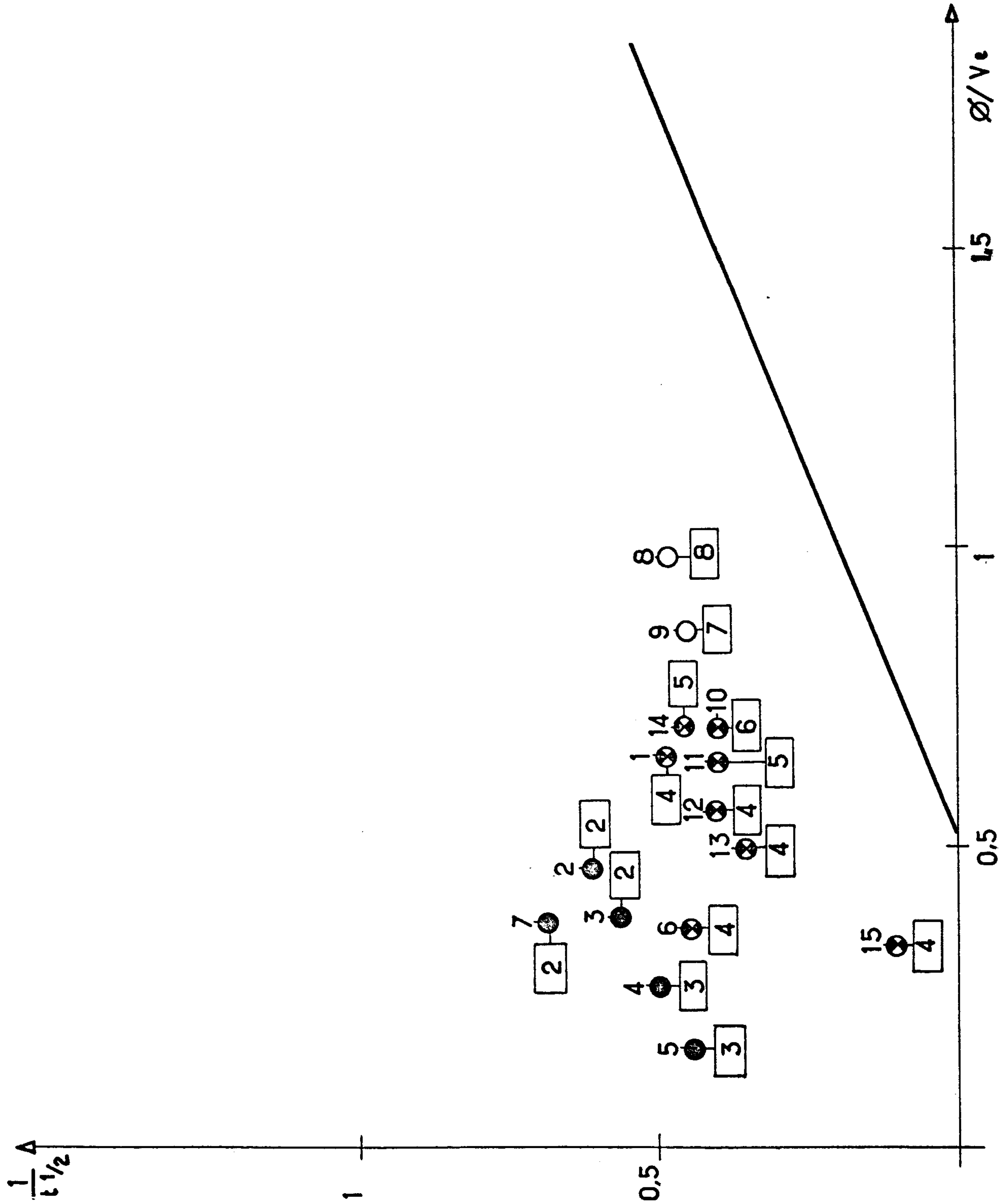


Figure 10

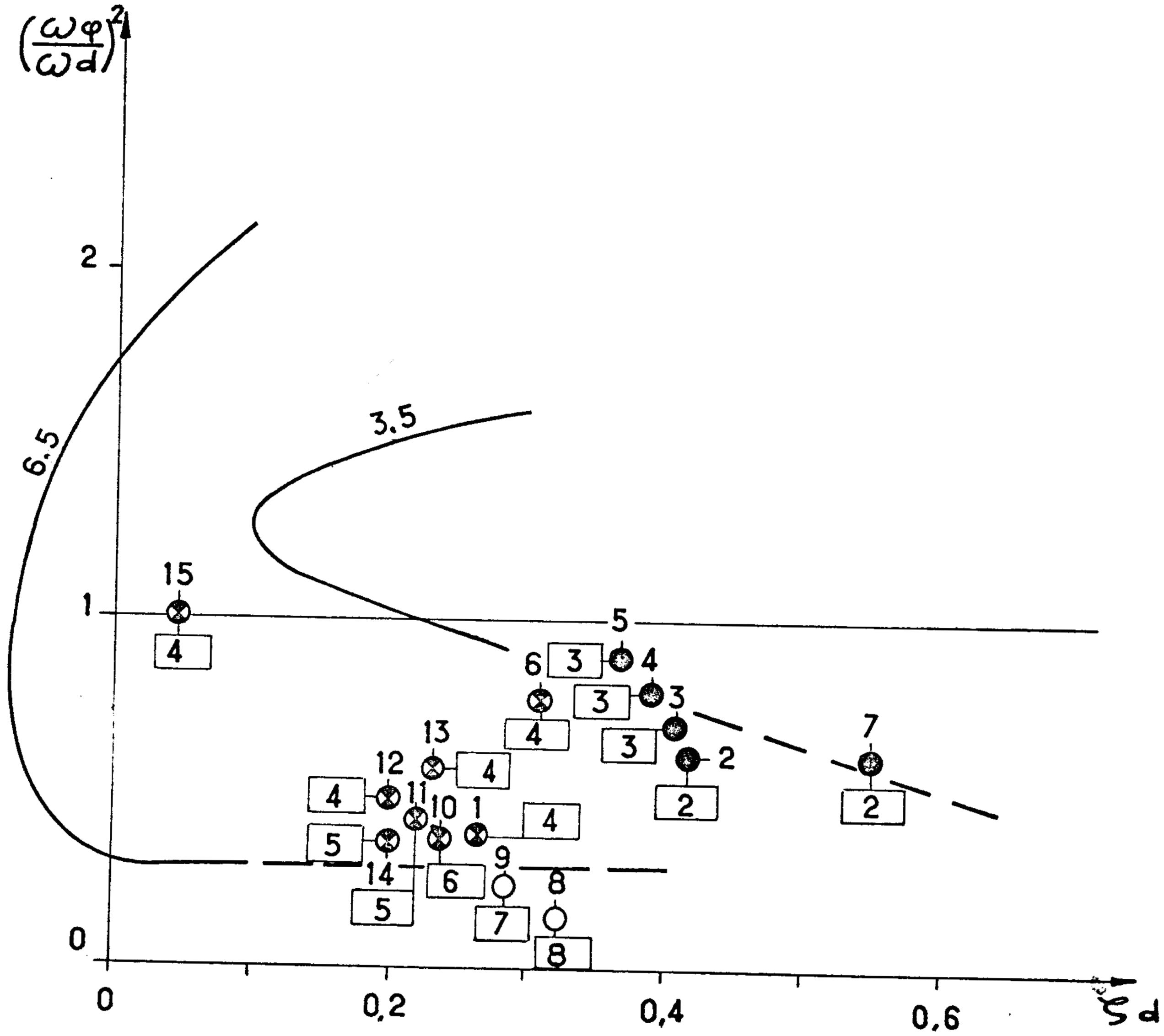

$\left(\frac{\omega\varphi}{\omega d}\right)^2$
2
1
0
0
0,2
0,4
0,6
ζd
6.5
3.5
15
4
5
3
4
6
3
3
4
3
13
4
12
4
2
7
11
10
1
4
5
2
2
14
6
9
8
5
7
8

Figure 11

(close to 3 s). Going over to time constants less than 0.5 s (for example by means of a roll damper) eliminates any problem.

One cannot be accurate about the "satisfactory" limit, but the experiment seems to confirm the existence of a small influence by the type of plane. It seems also that the values of 2 and 2.5 s considered in references 8 and 5 are too optimistic and that the limit is closer to 1.5 s (see fig. 9).

2. The spiral mode proper has never led to control problems. Let us mention that for time constants greater than 60 s the pilot becomes incapable of estimating the spiral stability (the effect being buried in the inaccuracy of the controls and of the balancers; see Section 1.2).

3. The free lateral oscillation has always seemed to be very damped. The possible difficulties here come from the coupling effects during the insertion of the pilot into the loop.

An examination of figures 9 through 11 permits to make additional remarks, as follow:

1. All the configurations tried check the criteria of figure 10 without necessarily entailing "good characteristics" for the airplane. /17

2. No case of flight where T_R is greater than 1 s is seen to be good, but this can be due, for points 1, 11, 12 and 13, to the approximation of the limits $|T_S\ |T_R\ | > 10$ or, rather, to the limits of figure 11.

3. A comparison of points 2, 3, 6 and 7 shows that below a certain value of T_R (0.5 s ?) the effect due to this variable is no longer felt. More precisely, the degradation felt when going from 2 to 6 can only be explained by changes of damping. All these results have a tendency to confirm the extrapolated criteria of figure 11.

4. The degradation of the pilot's judgement when going from 1 to 10 or from 13 to 14 seems to come essentially from the criterion of figure 9 (and also somewhat from that of figure 11 for the second case). The pilots mention difficulties in controlling the roll and the yaw. They also mention incoherences or phase shifts in these two quantities, and this confirms the undesirable coupling.

5. These are probably also the causes which make the cases 8 and 9 unacceptable, especially under turbulence. By comparison with the other cases, this conclusion cannot be due only to the value T_R of the roll time constant.

6. The notable preference given by pilots for the configurations 2, 3 and 7, as compared to configurations 4 and 5, is not explained by any of the above criteria. The reason offered is the roll-yaw inhomogeneity and shows perhaps that, on this type of airplane, too small values of ϕ / α provoke a certain discomfort.

2.4 The High Amplitude Maneuvers

We shall mention this question only to say that, however important for military planes, it becomes in practice for transport planes identical with the maneuvers examined in Section 3.5.

PART THREE. LONGITUDINAL FLIGHT QUALITIES

/18

In spite of the fact that many aspects of longitudinal flight qualities at high velocity would be worth discussing we have elected to examine, for lack of space, the low velocity flight case only. Under these conditions, only the problems connected with the accurate control of a flight path will be discussed.

3.1 Static Stability

The problem of the airplane longitudinal static stability is traditionally expressed in terms of remarkably simple criteria, as follows:

a) the "fixed stick" stability requires a displacement of the stick in order to obtain a lower stabilized velocity. This is normally equivalent to a positive static margin, in other words to an aerodynamic focus located behind the center of gravity.

b) the "free stick" stability requires exerting a pulling effort on the stick in order to obtain a lower velocity.

The necessity, or even the usefulness, of these two types of static stability depends strongly on the type and the mission of the airplane, and for the case of a transport plane two considerations are important. On one hand, in order to facilitate the work of the pilot, it is preferable that the plane, balanced for a chosen set of flight conditions, immediately return to them after a disturbance is applied. On the other hand, in order to facilitate the most versatile commercial use possible, it is preferable that the restrictions on the centering be as much reduced as possible.

The civilian standards accept the fixed stick instability (with certain /19 reservations, however, concerning approach or ascension following take-off). They require though, almost always, the free stick stability.

The special aspects introduced in the sections above by the highly swept plane seem to be the following:

- If one is interested in the fixed stick stability, then it is safe to discard the simple static margin criterion. Indeed, the notion of focus losses interest in general, since in addition to the thrust effect, a Mach effect can be felt down to the lowest approach velocities, together with the possibility of a dynamic pressure aeroelasticity effect. One must then, because of these two effects, not use the basic criterion $\frac{\delta\beta}{\delta V} > 0$.

- A strong factor will act to reduce this stability, whenever the flight qualities are not affected. This factor is its penalty in balance drag, which is relatively higher for a delta plane than for an airplane without tail structure. For a delta plane of 160 and 90 tons, at take-off and landing, respectively, with everything else being the same, a penalty of 2.5 to 3.0 tons must be paid for an increase in stability equivalent to a conventional 1 percent static margin.

- Since the plane must perform both in transonic and supersonic conditions, it has by necessity irreversible servo-control drives, and, almost certainly, a Mach compensator (balancer). The problem of free stick stability is (in general and including low velocities) more a flight control system problem than a special aerodynamic problem. This way of thinking assumes however that the breakdown ratio is sufficiently low and that the resulting flight quality deterioration is not dangerous. When the plane has in addition a control system for the center of gravity (by transferring the fuel), it is always possible if necessary to re-establish the natural static stability, by exceptionally accepting the corresponding performance penalty. It seems reasonable then to accept minimum static margins for normal operating conditions. /20

- Finally, but this is undoubtedly not the least important, the low velocity flights will take place well above the maximum aerodynamic efficiency. The performance under accurate flight path maintenance will lead to a marked instability under speed (2nd regime). This added difficulty may not be insurmountable, but is sufficiently strong to favor the widespread use of a remedy already available in the last conventional airplanes, namely the auto-handle. We shall return later to the dynamic aspect of this question. It seems important however to emphasize that the adoption of the auto-handle, which guarantees that a velocity chosen by the pilot will be maintained without surveillance and with a narrow margin, puts the problem of the static stability under approach conditions on a quite favorable and new basis. In addition, the problem of reasonable safety margins (of the kind V approach = 1.3 V_s) is again brought up, since the pilot no longer risks inadvertent sizable velocity excursions. If this point of view is adopted, nen the difficulty is shifted of course toward the breakdown ratio of the "Velocity detection and thrust control" loop. An almost fail-safe system is then mandatory with the last guarantee that the copilot must close the failing loop himself and the check that in any event the airplane is not exaggeratedly difficult to pilot.

3.2 Dynamic Stability

A few years ago the dynamic stability criteria which applied to civilian airplanes were remarkably scant It was generally required that the pitch angle oscillation, which was known to be of high frequency, be well damped, and that the phugoid oscillations have a sufficiently high period of oscillation, or otherwise that it be also damped. This broadmindedness did not prevent the operation of many generations of fairly satisfactory airplanes. The difficulties seem to have started with the first heavy jet planes. The statistics show in particular that the spreads in vertical speeds at impact and in flattening out lengths have increased markedly (Bray, ref. 14). Some studies were undertaken in order to obtain a better understanding of these effects.

3.2.1 Pitch Angle Oscillations

Systematic studies were carried out in flight and in simulator in order to determine the optimum conditions for the pitch oscillations. These studies were initiated by the Cornell Aeronautical Laboratory, by System Technology, Inc., and by the U.S.A.F.

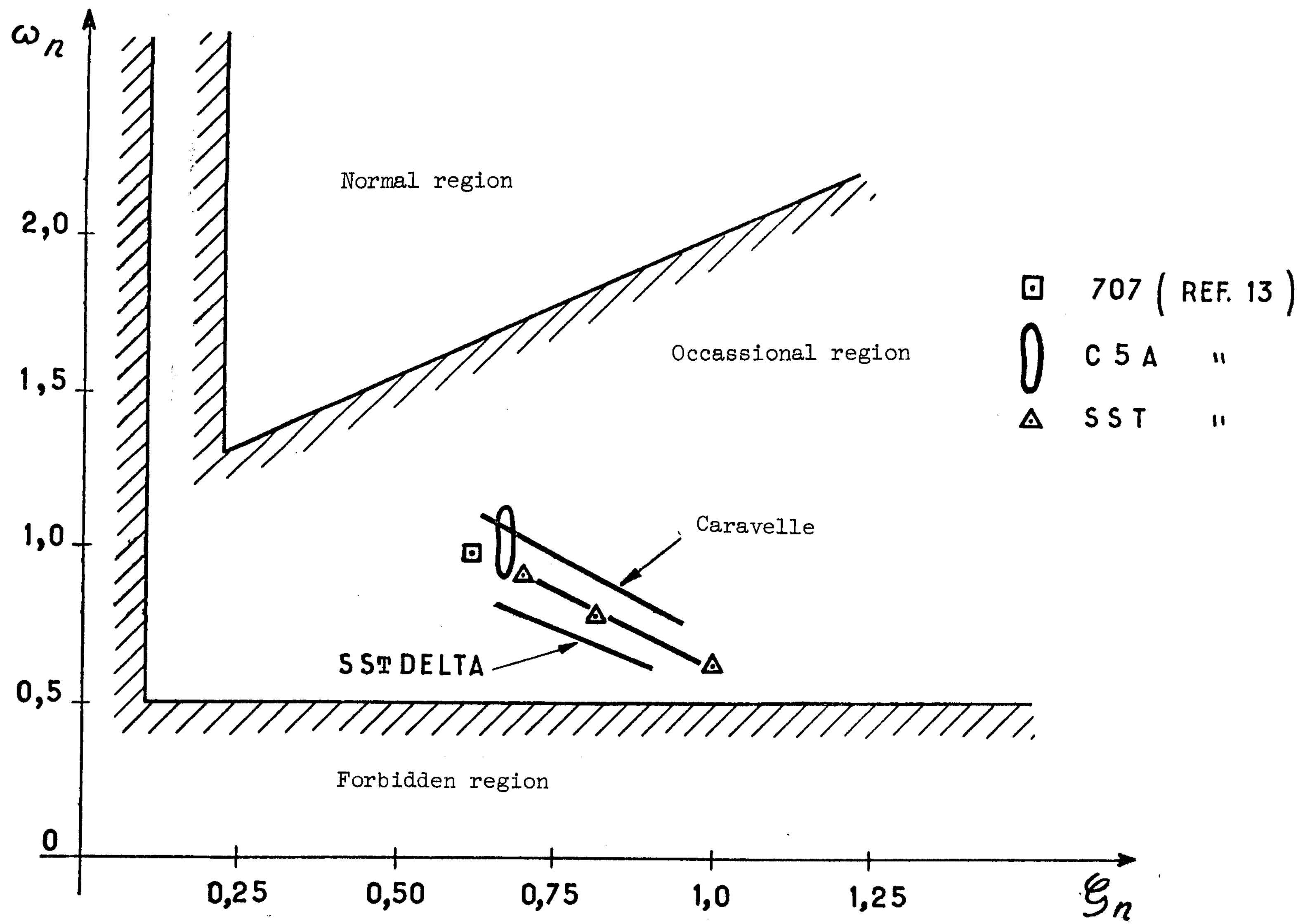
One was unfortunately tempted to generalize too much from the conclusions obtained for a fairly special case. Carlson (ref. 15) and Kehrer (ref. 18) have /21 emphasized this error, which we illustrate here again in figure 12. This shows clearly that the criteria proposed do not apply to the low speed flight of a heavy transport plane. Several reasons could be found to explain this disagreement, among which:

- Differences between the missions asked of the pilots

- Differences between the type of piloting: either 1 loop only (stick/attitude) for performances at relatively high velocity; or 2 loops (stick/attitude + thrust/speed or elevation) for performances at low approach speeds.

- An important but unknown effect of the airplane characteristics which does not show up in the ω_n, ξ_n plane.

Before going into the characteristics of swept planes it is necessary to comment here on the above disagreement. From many studies made on simulators, where pilots studied the behavior of a plane whose static margin and pitch damping were arbitrarily changed, the results obtained by SUD and BAC on two distinct groups of pilots can be mentioned. There is an extremely good agreement between the two series of tests. These results agree at least qualitatively with those of reference 16. They are represented in figure 13 and they show that the pilot seems in the first place to be sensitive to the maneuver margin. This therefore confirms qualitatively the usefulness of the proposed representation in the ω_n, ξ_n plane since the frequency and the maneuver margin are directly related. Figure 14 shows quantitatively however that the optimum region for transport planes seems to lie in ω_n much lower than predicted. Kehrer (ref. 18) and Shomber (ref. 17) give some very interesting comments on this topic. These led Shomber to propose a criterion in the plane $(\frac{L_i}{\omega_n}, \xi_n)$. L_i is approximately the reciprocal of the



ω_n
2,0
1,5
1,0
0,5
0
0,25
0,50
0,75
1,0
1,25
ξ_n
Normal region
Occassional region
Forbidden region
Caravelle
SST DELTA
707 (REF. 13)
C 5 A "
S S T "

Figure 12

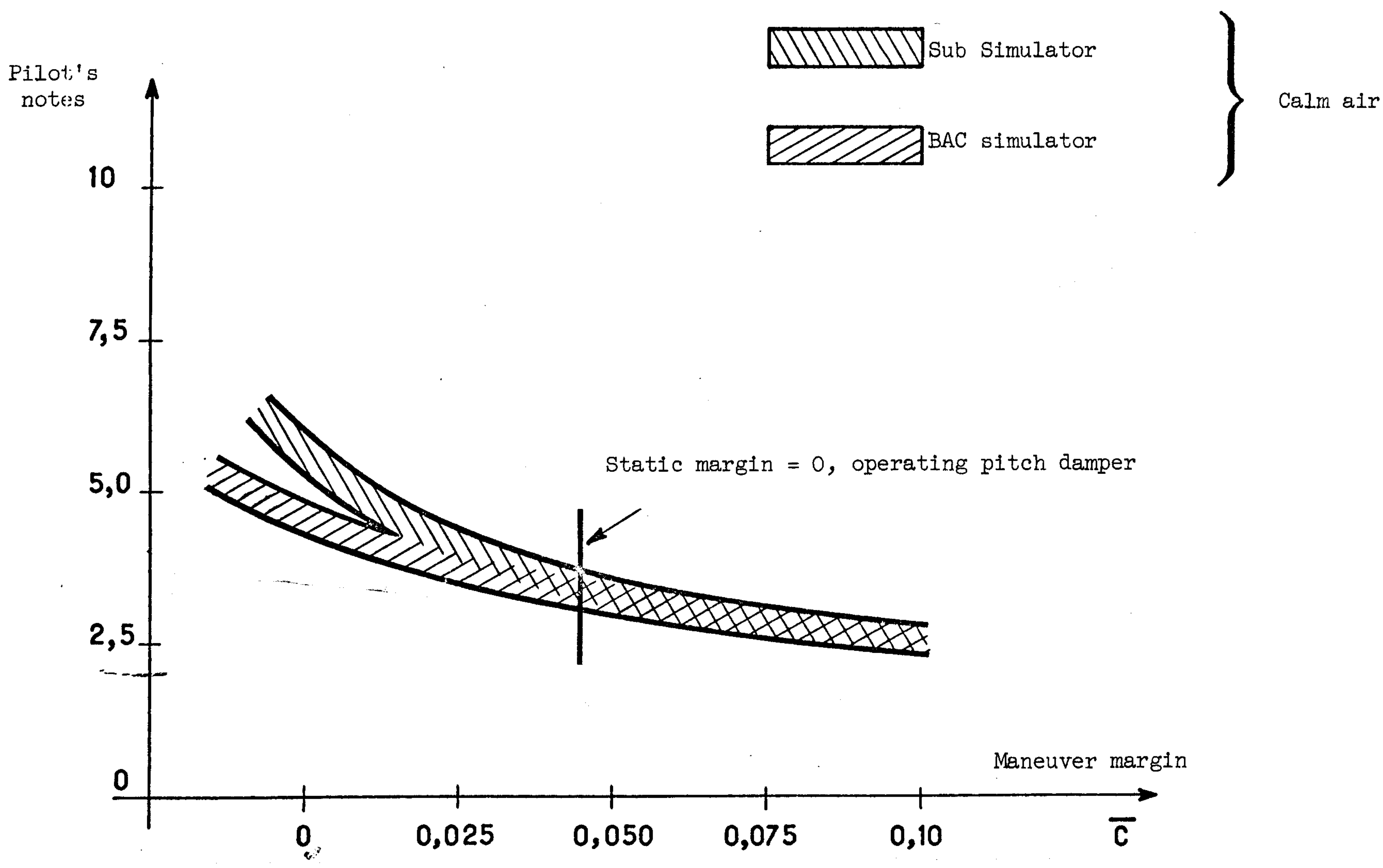

Pilot's notes
10
7,5
5,0
2,5
0
Sub Simulator
BAC simulator
Calm air
Static margin = 0, operating pitch damper
Maneuver margin
0
0,025
0,050
0,075
0,10
$\overline{C}$

Figure 13

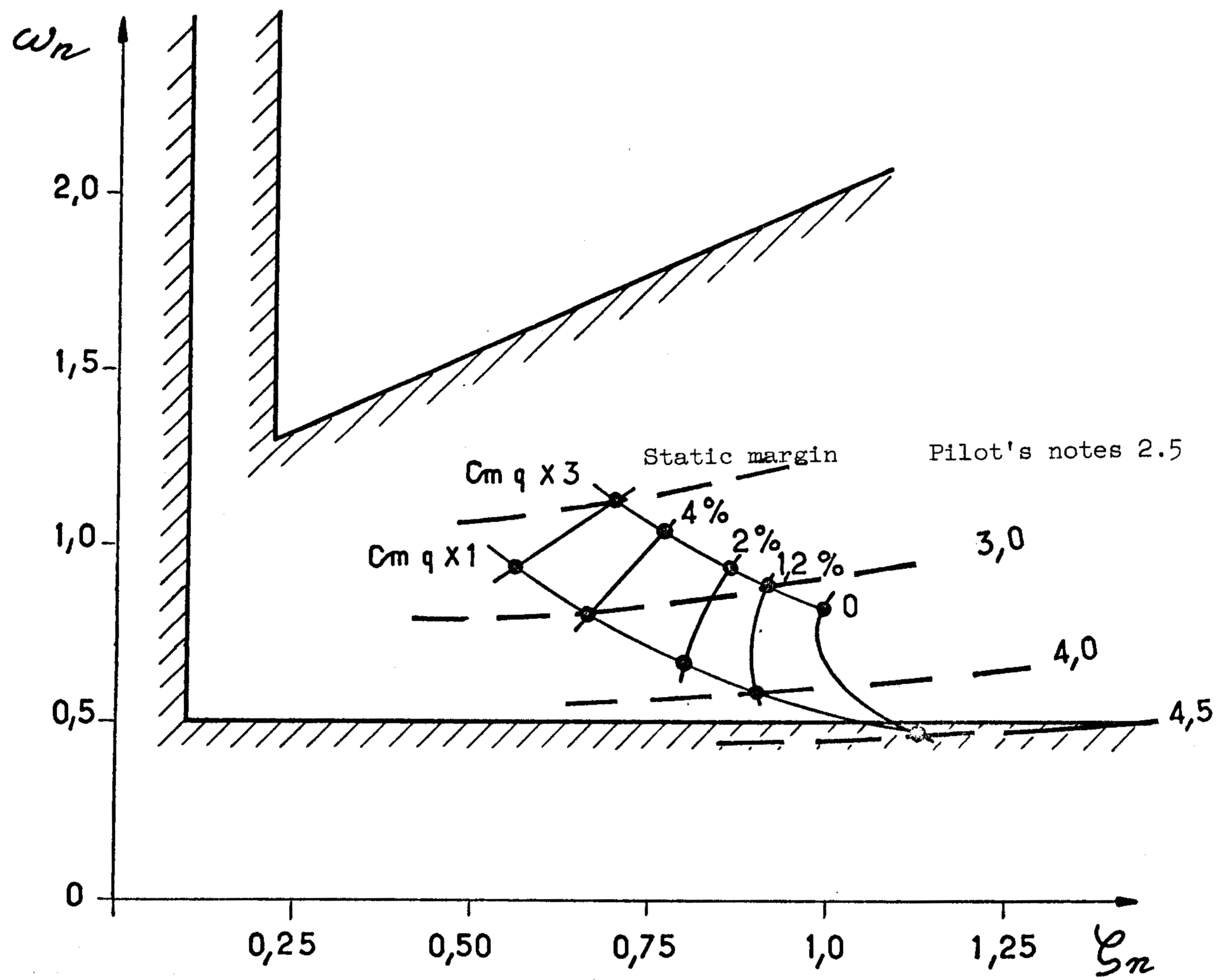

ω_n
2,0
1,5
1,0
0,5
0
0,25
0,50
0,75
1,0
1,25
ζ_n
Cm q X 3
Cm q X 1
Static margin
4 %
2 %
1,2 %
0
Pilot's notes 2.5
3,0
4,0
4,5

Figure 14

time constant which characterizes the slope change lag with respect to the attitude change. In spite of the fact that it is too soon to be able to judge the overall value of this last criterion, we think that it can represent a serious improve- /22 ment. Briefly speaking, this criterion consists in requiring that the reduced damping ξ_n, together with the ratio $\frac{L_i}{\omega_n}$, both remain within fairly narrow limits. The physical meaning is obvious as far as ξ_n is concerned. The parameter $\frac{L_i}{\omega_n}$ measures the overshoot of the transient pitch velocity above the stabilized velocity. The criterion requires therefore that the plane go rapidly toward its stabilized pitch velocity, without, however, having an overshoot greater than, say 50 percent (otherwise the pilot will have difficulties in adjusting for the attitude changes necessary for his corrections of flight path). Low values of ω_n become not only acceptable, but desirable when L_i is also low. Since low velocity and low $\frac{dC_z}{d_i}$ necessarily mean low L_i it is necessary to have for a transport plane in approach (and especially with swept wings) reduced values of ω_n. More studies are under way at SUD to apply the criterion to various configurations, for example to high-aspect ratio and moderately swept wings such as Caravelle, or conversely, to highly swept planes (fig. 17). Regardless of the future conclusions of these studies a certain number of comments must be made in regard to highly swept planes. In particular, since it has often been said that these planes were handicapped by: too large a pitch inertia; a reduced efficiency of the elevator (due to the low tail length); and a harmful lift interaction of the same elevator; it seems to us worthwhile to add some accuracy to these various points.

3.2.2 Pitch Inertia

It is obvious that this characteristic moves more and more in the wrong direction - i.e., it increases - but this tendency is essentially related to the weight increase and to the increase of commercial tonnage capacity. The highly swept

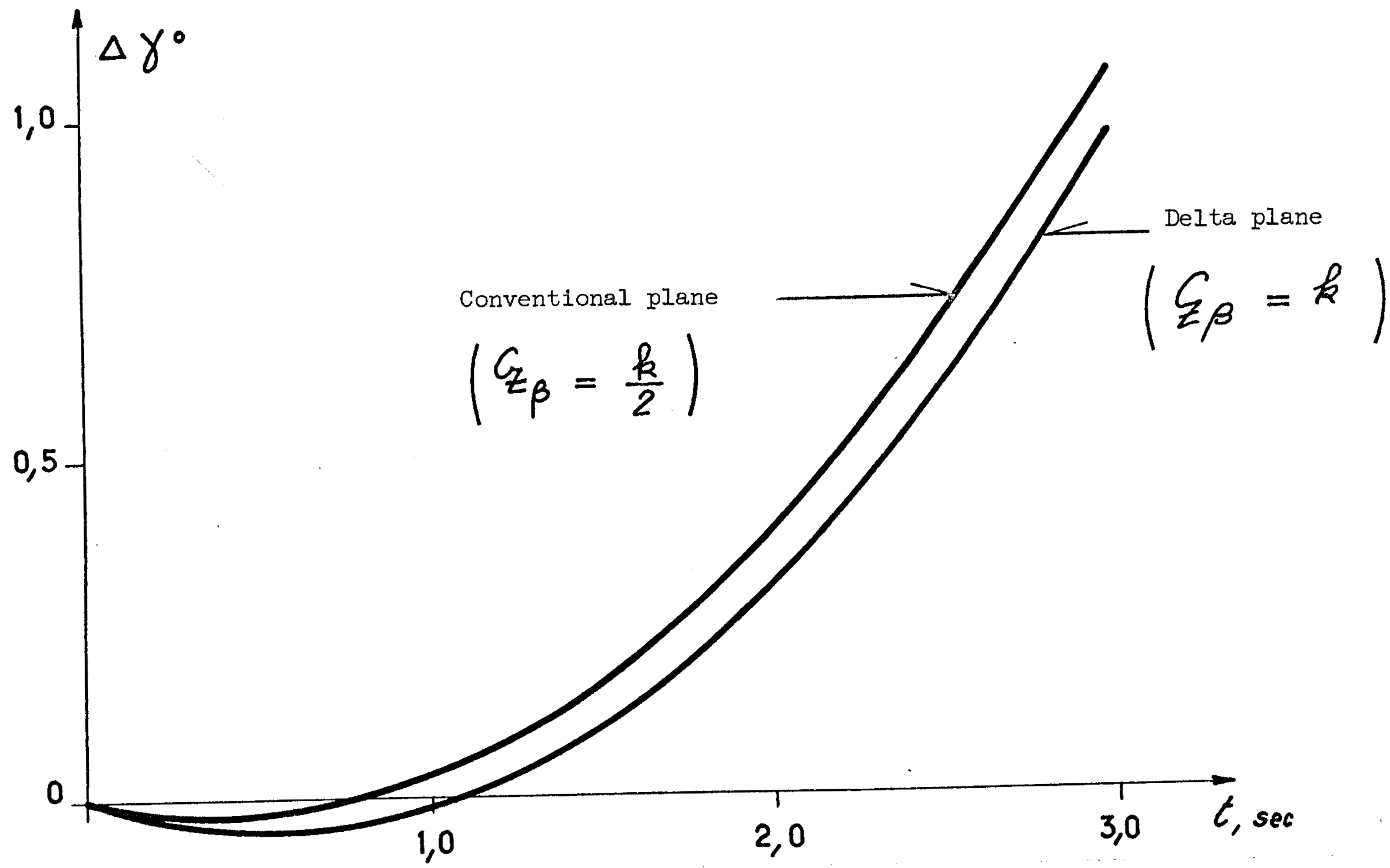

$\Delta \gamma^\circ$
1,0
0,5
0
1,0
2,0
3,0
t, sec
Conventional plane
$\left(C_{z_\beta} = \frac{k}{2} \right)$
Delta plane
$\left(C_{z_\beta} = k \right)$

Figure 15

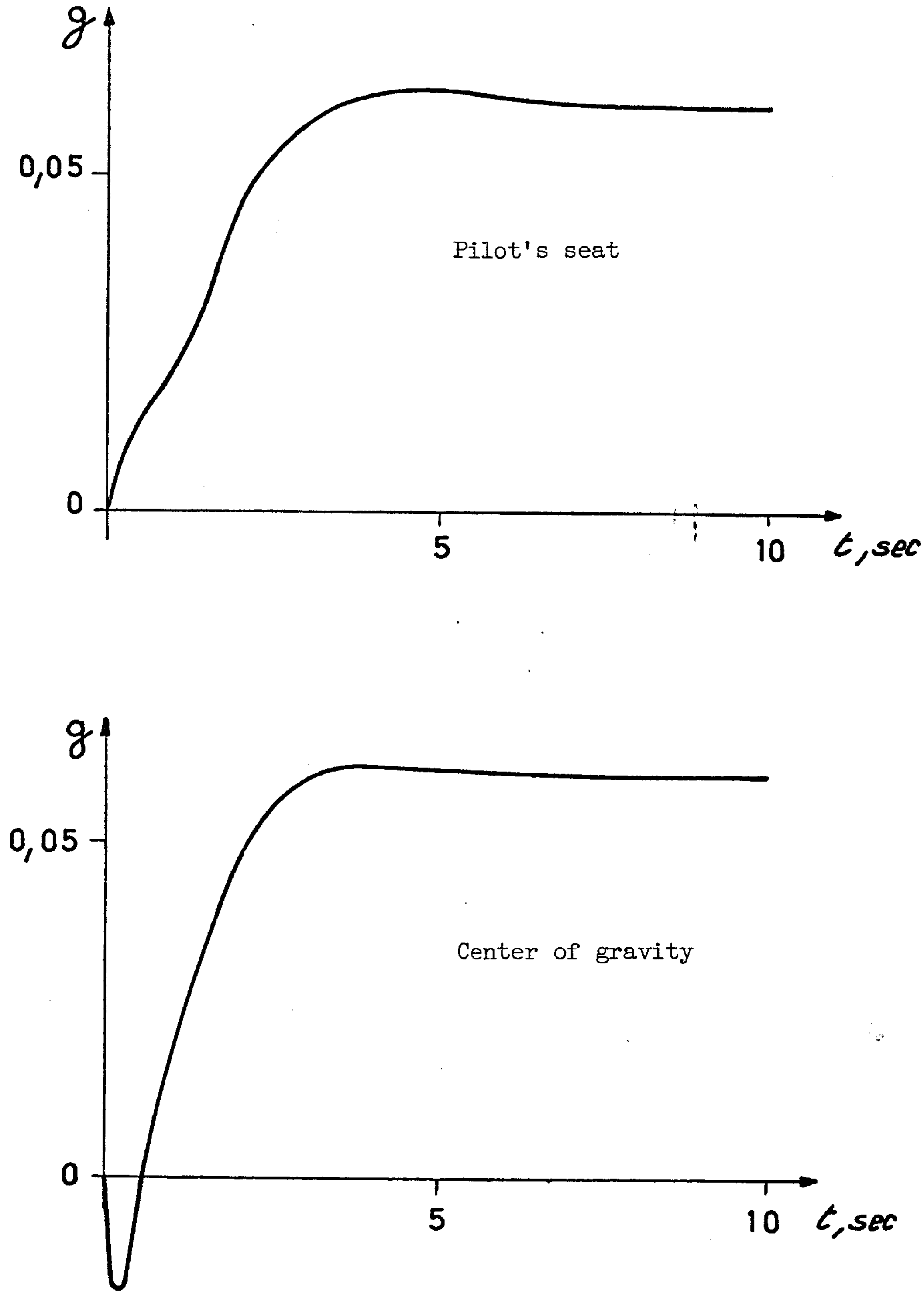


Figure 16

(a) Present subsonic planes (b) Delta plane with damper

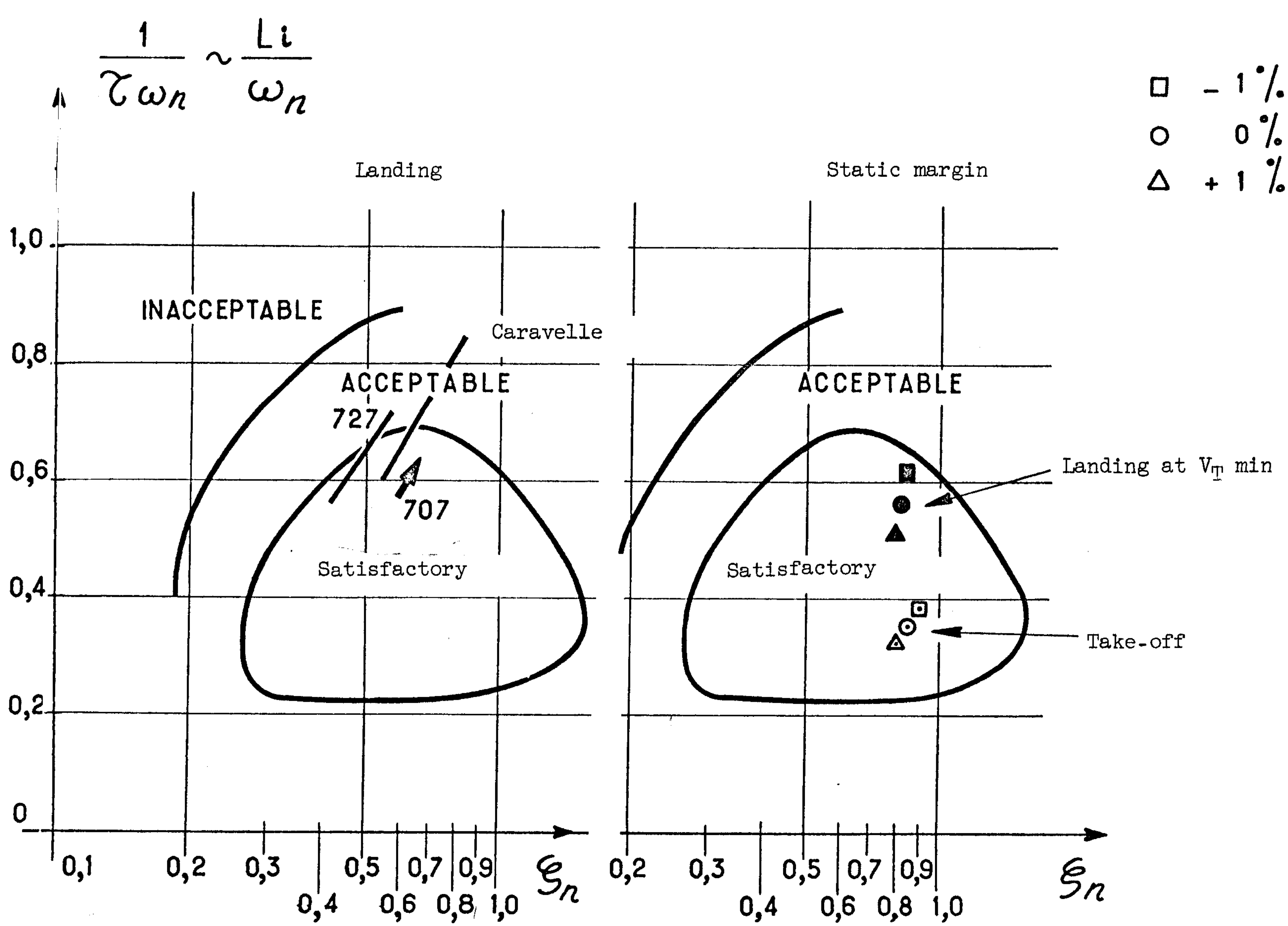


Figure 17

configurations, which are proper to supersonic speeds, aggravate for sure this drawback since they imply a more elongated fuselage for a given commercial /23 tonnage capacity. This is however a relatively secondary effect since none of the presently known supersonic projects reach values comparable to those of the heavy subsonic projects (Lockheed C5A, Boeing 747, Douglas DC 10 etc.). It can therefore be deduced that no exceptional difficulties will be encountered in the highly swept aircraft discussed here.

3.2.3 Pitch Efficiency

It should be emphasized that, contrary to a fairly widespread idea, the efficiency of an elevator of delta winged planes is generally better at low speeds than that of conventional planes. The surface area of these elevators, computed for transonic and supersonic performances, is indeed considerable (approximately 3 times greater for a subsonic plane of equivalent weight). In spite of the decrease in tail length the possibilities of angular acceleration are therefore improved in the end: Magruder and his collaborators (ref. 19) point out an increase of 40 percent of the available acceleration in the Lockheed project as compared to planes of the DC8/707 type. The increase is even greater for a plane of equivalent weight and this characteristic will be found to be extremely useful in all attempts to small and fast corrections of flight path the pilot may want to perform during approach.

3.2.4 Lift/Moment Opposition

It is of course a characteristic common to all planes having the control surfaces located behind the center of gravity to have a sign opposition between the change of lift force due to a deflection of the surface and the change of lift force sought by the pilot. The overall change reaches its correct sign only after a time interval during which the pitch has not changed sufficiently to counterbalance the immediate lift effect of the control surface. For a given efficiency this effect will be the greater the shorter the elevator tail length. The delta winged airplanes are therefore at a disadvantage compared to planes with tail surfaces, but in our studies we have not found an effect as high as the one indicated by Kehrer (ref. 18). For the characteristics of delta projects which we know, the flight path correction has a correct sign about one second after the start of the elevator deflection, and the maximum amplitude of the wrong sign displacement during this first period does not exceed a few centimeters per degree of deflection. In practice this effect is negligible, and even if the tail length is for example multiplied by 2, as it would be possible with a plane having a tail structure, the improvement would be too small to be of practical significance. This result is shown in figure 15. It can be added that, from the pilot's standpoint, an essential response is undoubtedly the acceleration of the pilot's seat and figure 16 shows that the transient effect of the elevator lift displacement is never detected. /24

Finally, assuming that the criterion proposed by Shomber is valid it can be shown that there is no difference between a delta plane and a plane with elevator provided the static margin is low. Indeed this criterion used the time constant, rigorously written as follows:

$$\frac{1}{\tau} = L_i - M_i \frac{M\beta}{M\beta}$$

which becomes L_i when L_{β} is low, as for the conventional plane. It is also clear that, even if the elevator lift term L_{β} is large then $\frac{1}{\tau}$ will approach L_i provided M_i, i.e., the static margin, goes to zero.

Using what was given above it could be concluded that, with its exceptional control efficiency, the delta plane will have satisfactory dynamic characteristics of short period provided it is suitably damped for low (positive or negative) static margins. These conclusions are (better than in fig. 14) confirmed in figure 17b (from the application of the Shomber criterion for a typical delta plane). In case of damper breakdown a zero static margin would lead however to a situation which would probably border the acceptable. The possibilities offered by a center of gravity control system will be welcome, as already mentioned above in regard to the static stability.

3.2.5 Phugoid Oscillation and 2nd Regime

The phugoid mode has so far drawn little attention, even when it leads to instabilities, because these are generally estimated not to be too bothersome to the pilot since their periods and their time constants are high. This is certainly true only if a speed or elevation must be maintained in a waiting lane. It would however be preferable that the pilot exert as relaxed a watch as possible in /25 order for him to devote himself to other tasks. This is no longer true for flight path controls of great precision, such as those considered increasingly in automatic, IFR, or visual landings. This precision will be increasingly hoped for, for both safety and performance reasons, so that a plane of the highest possible weight can be landed on a landing strip of given length.

The usefulness of the auto-handle for the precise maintenance of the flight path was, from this standpoint, already proved on subsonic planes such as H.S. Trident and Caravelle. Bisgood (ref. 21) thinks that, as far as the flight path speed stability is concerned, an airplane is satisfactory only if the time constant is less than 50 seconds. Exceptionally however (for example breakdown of the auto-handle), an instability with a time constant greater than 10 seconds[1] could be

[1]50 and 20 seconds, respectively for the SST Regulation No. 5

tolerated. The former condition is not met presently by conventional planes without auto-handle, whereas both are widely met by the delta plane with auto-handle.

On this point, as well as on the lift displacement of the elevators, it could be said that the theoretical disadvantage related to the shape of the polar curve of delta planes is only apparent. The auto-handle will not only restitute the handling to the first regime, i.e. to the simple stick/attitude loop. It will also damp the phugoid considerably. The importance of the latter becomes so apparent when a landing path must be faithfully repeated that Ashkenas (ref. 20) emphasizes the essential improvement which is made by the reduction of the static margin, this reduction having the effect of increasing the damping and period of the phugoid and of decoupling this mode from the pich oscillation. This result should be remembered, for example for the auto-handle breakdown case, in spite of the fact that the tests in this reference have to do with a case apparently very different from that of the normal approach of a transport plane (arrested /26 landing of 2nd regime on aircraft carriers). This leads to the opinion that in the final approach phase (including the flattening out) the zero static margin handling is preferable if the spread of point of impact must be low. It should be foreseen however that the transport plane pilot will accept this situation during the phase preceding the approach only if a good static stability is guaranteed him from other sources.

It is noteworthy that, concerning the center of gravity motions of large period, the constructor could be led to follow requirements which are more stringent than those of the various specifications. These must insure the safety and to a certain extent the ease of handling. For the take-off and approach phases the constructor must also worry to insure the best performance of his airplane, and this will depend in part on the handling precision. We therefore think it is a serious advantage for approach purposes to have characteristics much superior (because of the auto-handle) to those stipulated in the specifications, and his advantage will manifest itself fully during the certification of the airplane. In addition it seems that the advantages to expect from this device, including those mentioned in the Section "Static Stability", are about the same for all the transport planes. It can therefore be predicted that the use of this device will rapidly spread, now that the necessary technology has proved itself.

3.3 Comments on the Behavior Under Turbulence

The normal acceleration response in turbulence is, for the frequencies markedly higher than the pitch frequency, proportional to the L_i parameter mentioned above. A highly swept, low-aspect ratio, plane has of course a low lift gradient. With the high pitch angles tolerated we can have at approach a speed and a wing load of the same order of magnitude as that of conventional planes. The sensitivity to a gust will be reduced and the reduction can reach 30 to 40 percent as compared to present subsonic planes.

Near the pitch angle frequency the response depends also strongly on the static margin and increases markedly with the latter. This is a serious argument in favor of low static margin and low ω_n flights. It has been pushed forward during the previous discussions which the authors have had with Messrs. Ashkenas, McRuer Wasicko, Harper and Carlson (Brétigny, September 1963).

The two preceding comments permit us to think that not only the comfort /27
but also the safety will be improved from those of the present airplanes. In particular the stall or the divergence, whether spontaneous or provoked by a piloted surge (catastrophic examples of which are known, some in ascension, shortly after take-off) seen to be completely improbable. One must however not lose track

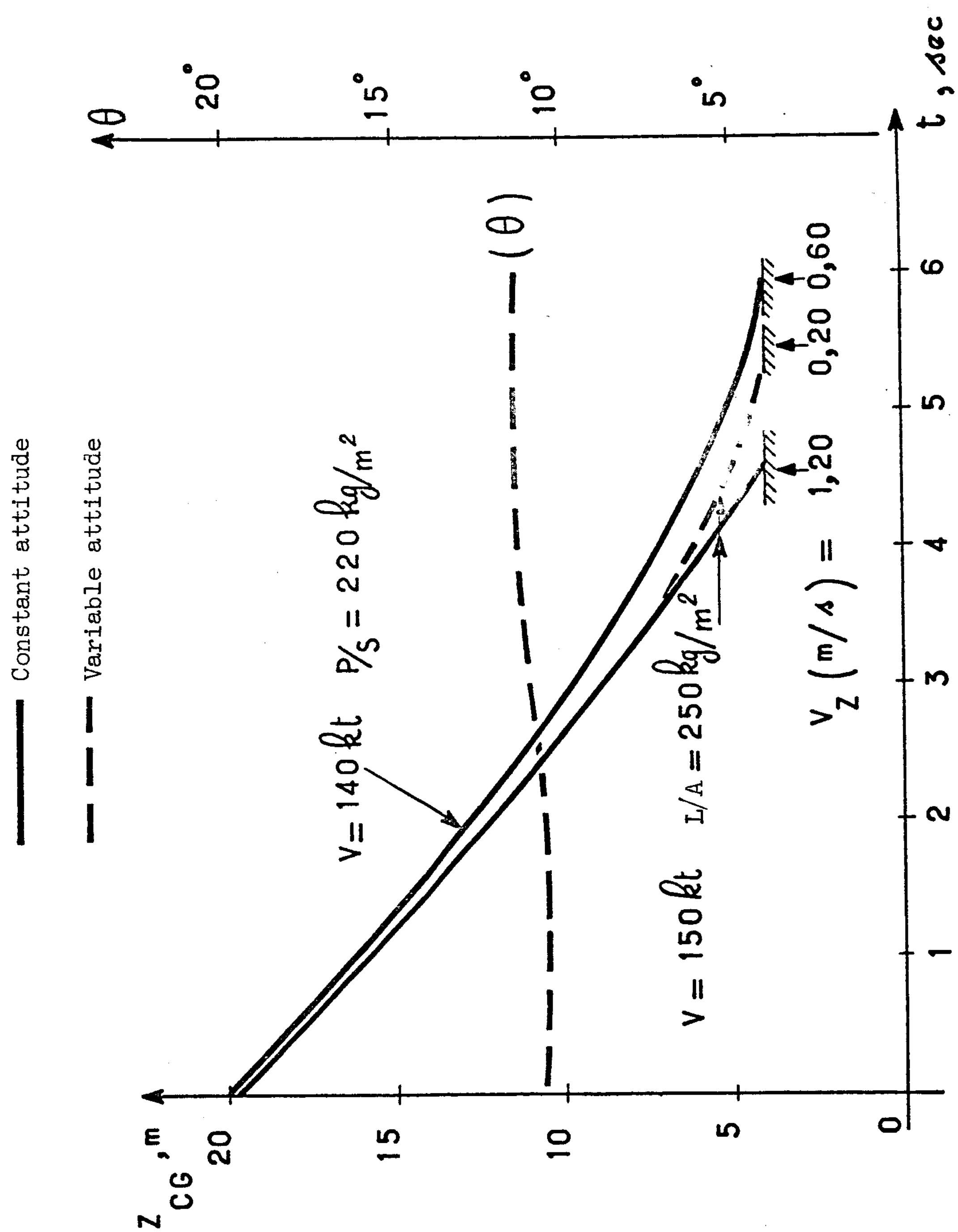
of the fact that for frequencies less than about $\frac{\omega_n}{2}$ a positive static margin is favorable because it has a tendency to resume the original pitch. A complete study is necessary for every plane and every special flight case.

3.4 Comments on the Landing

From all that was mentioned before, it can be deduced that the final landing maneuvers will be favorable to swept wing aircraft. A few additional comments are however useful.

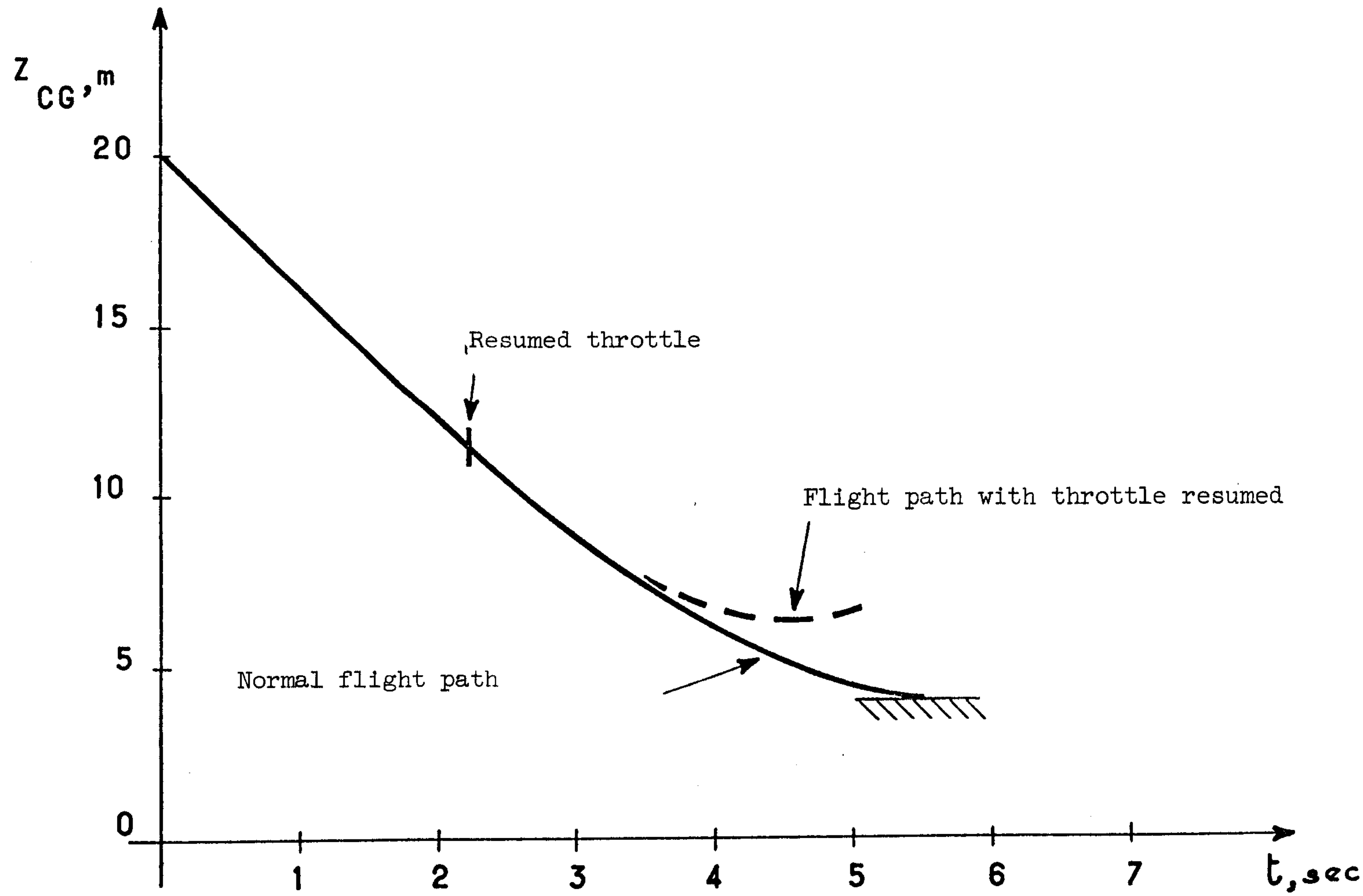
3.4.1 Ground Effects

An extremely favorable ground effect manifests itself just before the landing strip threshold (Z = 15 m approximately) for a plane whose mean chord is of about 20 to 30 meters. This effect entails a satisfactory flattening out of the plane provided the attitude is kept constant. In the unfavorable cases (velocity and high P/S (L/A)) an increase of 1^{o} in attitude is for this matter sufficient (fig. 18). The existence of this ground effect is now well established. This favorable effect cannot be accepted just from the wind tunnel tests alone. No mention will be made of the numerous military planes which use this effect every day. One can find however in reference 22 a very precise confirmation of this effect, obtained from test flights made by NASA. This means that important attitude corrections, which are the source of spread of impact characteristics, will not be necessary for the delta winged transport planes. It is true that the increase of balanced lift is accompanied by an increase of torque sinking the nose. This is however a maneuver where the pilot must anyway pull on the stick, and experience shows that he is not sensitive to this last increase of stability.



Constant attitude
Variable attitude
Z_{CG}, m
θ
t, sec
$V = 140$ kt
$P/S = 220$ kg/m²
$V = 150$ kt
L/A = 250 kg/m²
(θ)
V_Z (m/s) = 1,20 0,20 0,60

Figure 18



Z_{CG}, m
20
15
10
5
0
Resumed throttle
Flight path with throttle resumed
Normal flight path
1
2
3
4
5
6
7
t, sec

Figure 19

3.4.2 Resumption of Throttle

The case of the resumption of throttle to interrupt a landing is /28 another illustration of the advantage inherent to these planes. We have already mentioned that the fear of having a lift displacement on the elevator (by sudden deflection maneuver) was very exaggerated. When the pilot decides to interrupt the landing his only maneuver should then be "full throttle". The thrust response will be very rapid, due to the relatively high reactor operating regime. A jet lift will result (due to the pitch angle) which will be the greater the higher the available thrust.

Figure 19 shows that the combination of the lifts due to the ground effect and to the thrust effect permit the pilot to decide when exactly in the nominal path he can interrupt the final flattening out. The plane starts in most cases to undergo an ascension without having touched ground. The possibility of performing such a maneuver (which is of course exceptional) can only be favorable to an all-time operation.

PART FOUR

Conclusions

4.1 For the lateral case no simple flight handling quality has appeared /29 satisfactory by itself. Perhaps each criterion indicates a certain tendency, and the approach and the crossing of a limit leads almost always to a certain type of handling difficulties. This whole set of difficulties make up a useful guide, which should orient the studies and the research to improvements.

The whole set of criteria leads almost surely to a satisfactory plane but this "envelope" (rounding out) standpoint is perhaps needlessly severe. A situation fairly marginal with respect to one of the criteria could perhaps be compensated by a very favorable situation elsewhere.

The difficulty seems still greater for the unacceptable limits (required minimum during breakdown) where the criteria seem to be vaguer.

4.2 For the longitudinal case, the evolution of the existing or proposed criteria leads generally to a tightening of the regulations concerning the low velocity flight. The evolution results normally from a better understanding of the effects and from the need to increase the safety, the performance and the comfort.

The pitch angle oscillation and phugoid characteristics, together with the high velocity stability on a set flight path, are better narrowed down. These new requirements can, to a certain extent, be satisfactory for all planes only with the help of artificial devices (law of forces, dampers, auto-handle, etc.) which require a separate and involved study for the case of breakdown.

4.3 Even though they are quite different from their high aspect ratio, /30
swept wing, predecessors, the highly swept wing planes appear to be favorable from this new context. Their good spiral and oscillatory stability characteristics, their good control surface efficiency, their high ground effect, their low lift gradient and their very wide range of safe pitch angles are positive safety and comfort factors. The observed improvement obtained in going from an ordinary delta wing to a very highly swept wing is now well established, for example by the NASA test flights (ref. 22).

New problems require attention however. These are: the roll time constant, the coupling effects, the elevator lift, the second regime, etc. The present studies seem to show that the difficulties are modest, and that a good performance

TABLE 1

Flight Case	Practical Applications	Quality and Precision of Flight Controls	Efficiency of the Control Surfaces	
			Aileron α	Direction δ
Unpiloted plane controls free	Breakdown of auto or manual pilot. Maintenance of preset flight conditions. Normal conditions.	Important, especially in the roll		
Piloted plane balance	Possibility of nullifying the reactions. Normal and exceptional conditions.	Important, especially in the roll		
Precision handling	Maintenance of attitude and course. Precise flight path torque (approach)			
	Normal conditions........	....	....	....
	Exceptional conditions........	....	....	....
Change of flight regime	Various maneuvers (bayonet) + turbulence torque		Low velocity	Motor breakdown
	Normal........	....	60° in 6.5s	
	Exceptional........	....	6.0° 11s	

TABLE 1 (Continued)

Characteristics in Permanently Slipped Flight	Roll Mode T_R	Spiral Mode T_S	Oscillatory Mode ζd ωd Num ζ_ϕ ω_ϕ
Favorably high aerodynamic stiffness Clj Cnj		Should not be too unstable. Unstable T_S about 22s	Must have a minimum amount of damping
Favorably high aerodynamic stiffness			
....	T_R not too large for example ... $T_R \leq 1.5s$ ... $T_R \leq 8s$?	Reduced coupling between spiral and roll or oscillation $\lvert T_S \rvert > 10$ $\lvert T_S/T_R \rvert > 10$. No precise limit?	Criteria setting the acceptable damping in normal (ζd) and exceptional conditions and the coupling ratio ϕ/V_e P/r ω_ϕ/ω_d
Greater sensitivity to turbulence if Clj and Cnj are large		Necessary greater aileron control if T_R is large	

TABLE 2. TYPICAL BEHAVIOR OF SWEPT HEAVY PLANES.

Flight Case	Practical Applications	Quality and Precision of Flight Controls	Efficiency of Control Surfaces	Slipped flight	Roll Mode T_R	Spiral Mode T_S	Oscillatory Mode
Unpiloted plane free controls				Good characteristics Clj and Cnj large		Very stable	Always well damped
Piloted plane balance	Possibility of nullfying the reactions	Ditto	Favorable characteristics				
Precision handling	Normal	....	....	....	$T_R<1.5$ with auto-stabilizer	$\lvert T_S\rvert>10$ $\lvert T_R/T_S\rvert>10$ <u>Good</u>	ζd criteria in ϕ/V_e p/r, ω_ϕ/ω_d. Met for normal and exceptional <u>Good</u>
	Exceptional..........	....	....	....	$T_R \ll 8$ however $T_R>$ old planes		
Change of flight regime			Great efficiency of ailerons n necessary at low velocity (Clj) otherwise greater than necessary	Sensitivity to roll in turbulence (Clj)	Fairly high T_R hence necessary sufficiently high efficiency especially without auto-stabilization		

flight-handling-qualities compromise may be found, perhaps with the help in part of artificial devices not having seemingly critical breakdowns.

4.4 The complexity of the problems is however such that a more intelligent and more final opinion will be possible only when a sufficient number of tests will be performed with simulator, variable stability planes and, above all, with true flights.

The authors wish to thank all their colleagues at SUD AVIATION, specialists of flight handing qualities, whose work is the basis of the present study. They also wish to thank the technical management of this company who has consented to release the present report for publication.

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NOTATION

		Usual corresponding U. S. Notation
i	Pitch (Incidence)	α
j	Slip (Dérapage)	β
α	Aileron deflection (Braquage du gauchissement)	δ_a
β	Elevator deflection (Braquage de la profondeur)	δ_e
C_x	Aerodynamic drag coefficient (Coefficient aérodynamique de traînée)	C_D
C_z	Aerodynamic lift coefficient (Coefficient aérodynamique de portance)	C_L
C_l, C_m, C_n	Coefficients of roll, pitch and yaw moments (Coefficients de moment de roulis, tangage et lacet	C_l, C_m, C_n
p, q, r	Angular velocities of roll, pitch and yaw (Vitesses angulaires de roulis, tangage et lacet)	p, q, r
V_c		V_c
V_D		V_D
V_s	Stall velocity (Vitesse de décrochage)	V_s
V_e	Lateral velocity (Vitesse "transversale" (jV)	V_e
T_R	Time constant of the pure roll mode (Constante de temps du mode de roulis pur)	T_R

		Usual corresponding U. S. Notation
T_s	Time constant of the spiral mode (Constante de temps du mode spiral)	T_s
ωd, ζd	Frequency and damping of the oscillatory mode (Pulsation et amortissement du mode oscillatoire)	ωd, ζd
$\omega\phi$, $\zeta\phi$	Terms in the numerators of the transfer function p/α (Termes intervenant au) numèrateur de la fonction de transfert p/α)	$\omega\phi$, $\zeta\phi$
ωn, ζn	Frequency and damping of the pitch oscillation (Pulsation et amortissement de l'oscillation d'incidence)	ωn, ζn
ϕ	Lateral attitude (Assiette transversale)	
L_i =	$\frac{\rho SV}{2m} \times \frac{\delta C_z}{\delta i}$	$L\alpha$
L_β =	$\frac{\rho SV}{2m} \times \frac{\delta C_z}{\delta \beta}$	$L\delta$
M_β	$\frac{\rho S l V^2}{I} \times \frac{\delta C_m}{\delta \beta}$	$M\delta$